TABLE OF EXHIBITS
WaterLegacy Objections to PolyMet Draft Permit to Mine

Exhibit 17	B. Johnson, Summary Analysis of PolyMet NorthMet Modeled Tailings Chemistry and MinnAMAX Site Tailings Leachate (Dec. 2015)
Exhibit 18	J. Lupo, Ph.D., P.E., Dry Stack Tailings Overview, Slide Presentation excerpts (2012)
Exhibit 19	J.D. Lehr, Technical Memorandum - Summary of Comments Resulting from Review of NorthMet Mining Project and Land Exchange Supplemental Draft Environmental Impact Statement with Figures (Mar. 12, 2014)
Exhibit 20	A. Runkel, Comment on the NorthMet Supplemental Draft Environmental Impact Statement (Mar. 13, 2014)
Exhibit 21	D. Lee, Ph.D., P.E., PolyMet Tailings Basin Performance (Dec. 10, 2015)
Exhibit 22	Barr, Groundwater Containment System: Degree of Use in Industry (Dec. 26, 2012)
Exhibit 23	B. Weber, Federal study says oil sands toxins are leaching into groundwater, Athabasca River, Edmonton Globe and Mail (Feb. 20, 2014)
Exhibit 24	Frank et al., Profiling Oil Sands Mixtures from Industrial Developments and Natural Groundwaters for Source Identification, *Env. Sci. & Tech*. (Jan. 21, 2014)
Exhibit 25	K. Orland, The battle over when and how to clean up oilsands tailings ponds is escalating, *Calgary Herald* (Jan. 16, 2018)
Exhibit 26	D. Lee, PolyMet Category 1 Waste Rock Stockpile (Dec. 10, 2015)
Exhibit 27	PolyMet PTM Application, Figure 11-5, Project Water Balance in Mine Year 10 (Dec. 2017)
Exhibit 28	Sutton (Spectrum Eng.), email to D. Dostert (DNR) re PolyMet Tailings Wet Closure (Jan.23, 2012)
Exhibit 29	M. Malusis, Comments on Draft Dam Safety Permit 2016-1380 (Flotation Tailings Basin), Updated Permit Application Documents, and Outstanding Permit Issues (Oct. 12, 2017)
Exhibit 30	Myrbo, et al., Increase in nutrients, mercury, and methylmercury as a consequence of elevated sulfate reduction to sulfide in experimental wetland mesocosms, *J. Geophys. Research: Biogeosciences*, 122 (2017*)*
Exhibit 31	U.S. Geological Survey, Floods of June 2012 in Northeastern Minnesota (2012)
Exhibit 32	Barr Memo, FTB (Flotation Tailings Basin) Dam Break Analysis, Figure 3 (Dec. 4, 2012)
Exhibit 33	PolyMet FEIS, Figure 4.2.2-18, Residential Wells (2015)
Exhibit 34	Barr, HRF (Hydrometallurgical Residue Facility) Dam Break Analysis (July 11, 2016)

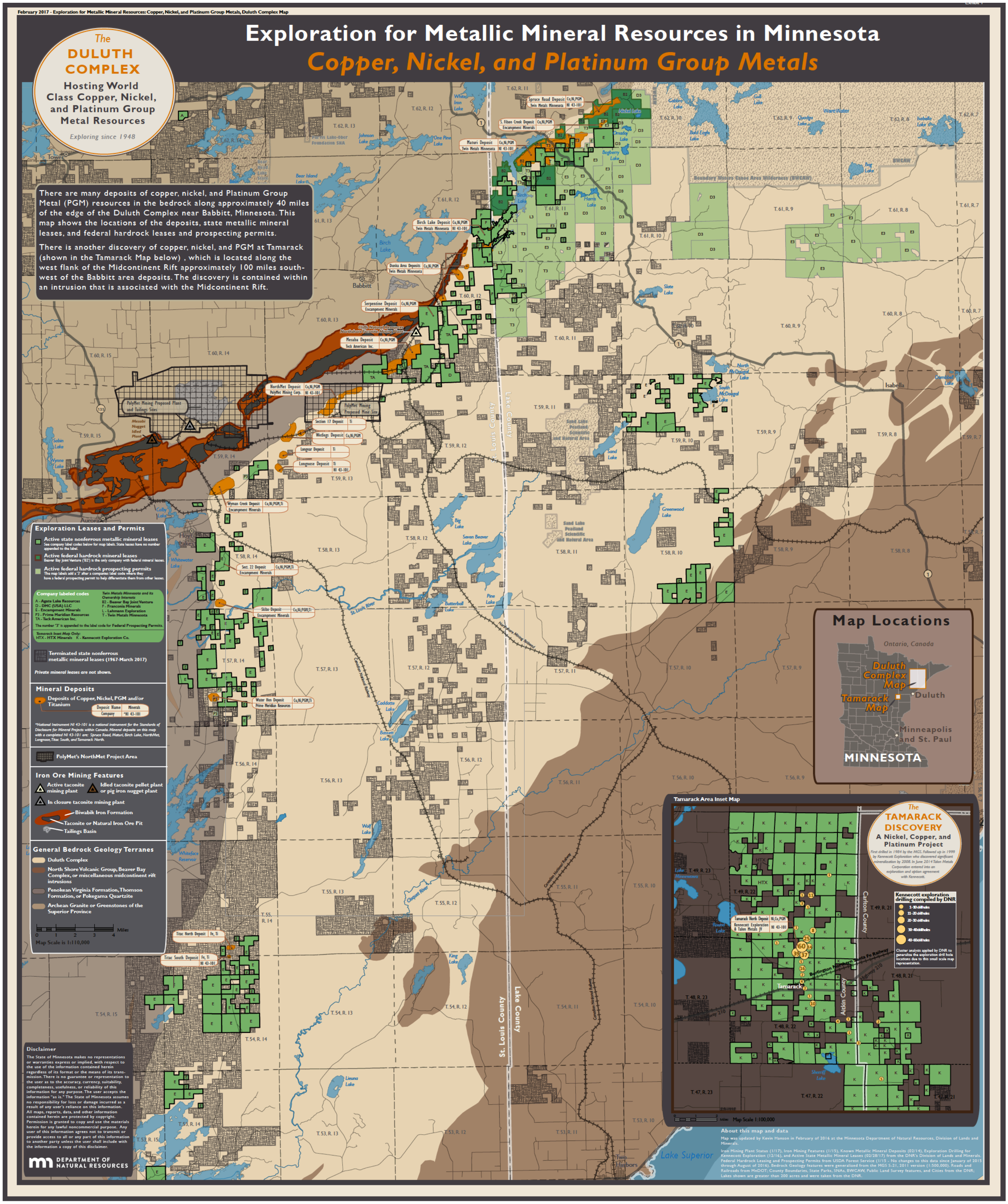
Exhibit 35	L.N. Bowker and D. Chambers, The Risk, Public Liability & Economics of Tailings Storage Facility Failures (July 21, 2015)
Exhibit 36	L.N. Bowker and D. Chambers, In the Dark Shadow of the Supercycle Tailings Failure Risk & Public Liability Reach All Time Highs, *Environments* 4. 7 (2017)
Exhibit 37	WISE, Chronology of major tailings dam failures (from 1960), (updated July 8, 2017)
Exhibit 38	B. Machlis, A Win For The Mining Industry: EPA Declines To Impose CERCLA 108(b) Financial Responsibility Requirements, Dorsey & Whitney, LLP, Publications (Dec. 4, 2017)
Exhibit 39	EPA, CERCLA Section 108(b) Financial Responsibility, A public webinar hosted by the United States Environmental Protection Agency (May 17, 2016)
Exhibit 40	EPA, *Financial Responsibility Requirements Under CERCLA §108(b) for Classes of Facilities in the Hardrock Mining Industry*, 82 FR 3388 (Jan. 11, 2017)
Exhibit 41	Ann Foss, MPCA Metallic Mining Sector Director, Legacy Permitting/Financial Assurance for Change in Assignment Former LTV Steel Mining Company (LTVSMC) Tailings Basin and Plant Site (Dec. 12, 2017)
Exhibit 42	*In the Matter of the Proposed Rules of the Pollution Control Agency Amending the Sulfate Water Quality Standard Applicable to Wild Rice and Identification of Wild Rice Rivers,* Report of the Administrative Law Judge (Jan. 9, 2018)
Exhibit 43	Environmental Groups' Comments on MPCA 2017 Triennial Standards Review (Feb. 9, 2018)
Exhibit 44	EPA (T. Hyde), Letter to Sen. Bakk and Rep. Dill (May 13, 2011)
Exhibit 45	MPCA, MPCA Wild Rice Sulfate Standard (updated 1/28/13)
Exhibit 46	*State v. Halvorsen*, 2017 Minn. App. Unpub. LEXIS 31; 2017 WL 84146 (Minn. Ct. App. Jan. 9, 2017)
Exhibit 47	MPCA, Draft Impaired Waters List 2018, excerpt with St. Louis River, Lake Superior Basin 2018 Mercury Impaired Waters (2018)
Exhibit 48	Barr, Hydrogeology of Fractured Bedrock in the Vicinity of the NorthMet Project, Large Figures 1-2 (Dec. 2014)
Exhibit 49	B. Johnson, A Review of the PolyMet NorthMet Supplementary Draft Environmental Impact Statement and Selected Supporting Documents Related to the Predictions of Solute Levels in Discharge (Mar. 2014)
Exhibit 50	GLIFWC email to MDNR et al. Bedrock-Wetland Connections at PolyMet Mine Site (July 29, 2015)
Exhibit 51	GLIFWC letter to Co-Lead Agencies Northward Flowpath & Modeling (Aug. 11, 2015)

Exhibit 52 GLIFWC letter to Co-Lead Agencies Discharge from PolyMet East Pit at Closure (Oct. 20, 2015)

Exhibit 53 Northshore Mining Company Environmental Assessment Worksheet (2014)

Exhibit 54 DNR et al., Technical Memorandum, NorthMet EIS Co-lead Agencies' Consideration of Possible Mine Site Bedrock Northward Flowpath (Oct. 12, 2015)

Exhibit 55 EPA, Letter and Detailed Comments on the NorthMet Mine Final Environmental Impact Statement (Dec. 21, 2015)


February 2017 - Exploration for Metallic Mineral Resources: Copper, Nickel, and Platinum Group Metals, Duluth Complex Map
Exploration for Metallic Mineral Resources in Minnesota
Copper, Nickel, and Platinum Group Metals
The DULUTH COMPLEX
Hosting World Class Copper, Nickel, and Platinum Group Metal Resources
Exploring since 1948
There are many deposits of copper, nickel, and Platinum Group Metal (PGM) resources in the bedrock along approximately 40 miles of the edge of the Duluth Complex near Babbitt, Minnesota. This map shows the locations of the deposits, state metallic mineral leases, and federal hardrock leases and prospecting permits.
There is another discovery of copper, nickel, and PGM at Tamarack (shown in the Tamarack Map below), which is located along the west flank of the Midcontinent Rift approximately 100 miles southwest of the Babbitt area deposits. The discovery is contained within an intrusion that is associated with the Midcontinent Rift.
Exploration Leases and Permits
Active state nonferrous metallic mineral leases
See company label codes below for map labels. State leases have no number appended to the label.
Active federal hardrock mineral leases
Beaver Bay Joint Venture ('B2') is the only company with federal mineral leases.
Active federal hardrock prospecting permits
The map labels add a '3' after a companies label code where they have a federal prospecting permit to help differentiate them from other leases.
Company labeled codes
A - Agate Lake Resources
D - DMC (USA) LLC
E - Encampment Minerals
P3 - Prime Meridian Resources
TA - Teck American Inc.
Twin Metals Minnesota and its Ownership Interests
B2 - Beaver Bay Joint Venture
F - Franconia Minerals
L - Lehmann Exploration
T - Twin Metals Minnesota
The number '3' is appended to the label code for Federal Prospecting Permits.
Tamarack Inset Map Only:
HTX - HTX Minerals K - Kennecott Exploration Co.
Terminated state nonferrous metallic mineral leases (1967-March 2017)
Private mineral leases are not shown.
Mineral Deposits
Deposits of Copper, Nickel, PGM and/or Titanium
Deposit Name
Minerals
Company
*NI 43-101
*National Instrument NI 43-101 is a national instrument for the Standards of Disclosure for Mineral Projects within Canada. Mineral deposits on this map with a completed NI 43-101 are: Spruce Road, Maturi, Birch Lake, NorthMet, Longnose, Titac South, and Tamarack North.
PolyMet's NorthMet Project Area
Iron Ore Mining Features
Active taconite mining plant
Idled taconite pellet plant or pig iron nugget plant
In closure taconite mining plant
Biwabik Iron Formation
Taconite or Natural Iron Ore Pit
Tailings Basin
General Bedrock Geology Terranes
Duluth Complex
North Shore Volcanic Group, Beaver Bay Complex, or miscellaneous midcontinent rift intrusions
Penokean Virginia Formation, Thomson Formation, or Pokegama Quartzite
Archean Granite or Greenstones of the Superior Province
0 1 2 3 4 Miles
Map Scale is 1:110,000
Disclaimer
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DEPARTMENT OF NATURAL RESOURCES
Map Locations
Ontario, Canada
Duluth Complex Map
Tamarack Map
Duluth
Minneapolis and St. Paul
MINNESOTA
Tamarack Area Inset Map
The TAMARACK DISCOVERY
A Nickel, Copper, and Platinum Project
Kennecott exploration drilling compiled by DNR
Map Scale 1:100,000
St. Louis County
Lake County
Carlton County
Aitkin County
Lake Superior
Babbitt
Aurora
Isabella
Two Harbors
About this map and data
Map was updated by Kevin Hanson in February of 2016 at the Minnesota Department of Natural Resources, Division of Lands and Minerals.
Iron Mining Plant Status (1/17), Iron Mining Features (1/15), Known Metallic Mineral Deposits (02/14), Exploration Drilling for Kennecott Exploration (12/16), and Active State Metallic Mineral Leases (02/28/17) from the DNR's Division of Lands and Minerals. Federal Hardrock Leasing and Prospecting Permits from USDA Forest Service (1/15 - No changes to this data since January of 2015 through August of 2016). Bedrock Geology features were generalized from the MGS S-21, 2011 version (1:500,000). Roads and Railroads from MnDOT; County Boundaries, State Parks, SNAs, BWCAW, Public Land Survey features, and Cities from the DNR; Lakes shown are greater than 200 acres and were taken from the DNR.

Certified Product Notification Forms. Award applicants are estimated to spend an additional 20 hours on average to complete the awards application. Burden means the total time, effort, or financial resources expended by persons to generate, maintain, retain, or disclose or provide information to or for a Federal agency. This includes the time needed to review instructions; develop, acquire, install, and utilize technology and systems for the purposes of collecting, validating, and verifying information, processing and maintaining information, and disclosing and providing information; adjust the existing ways to comply with any previously applicable instructions and requirements which have subsequently changed; train personnel to be able to respond to a collection of information; search data sources; complete and review the collection of information; and transmit or otherwise disclose the information.

The ICR provides a detailed explanation of the Agency's estimate, which is only briefly summarized here:

Estimated Number of Respondents: 357 state and local government; 1,319 private sector organizations, and 668 individuals per year.

Frequency of Response: Varies.

Estimated Total Annual Hour Burden: 57,248 hours.

Estimated Total Annual Cost: $4,665,618, including $1,793,181 in operation & maintenance costs.

Are There Changes in the Estimates From the Last Approval?

The overall burden estimate for this collection is 7,167 hours higher than the burden estimated under the current ICR because the WaterSense program has been launched and expanded since the current ICR was approved. The change in burden reflects the substantial increase in the number of products certified, new partners joining and reporting, and the addition of the New Homes portion of the program. EPA also has a better understanding of how long it takes partners to complete program forms, now that the program is underway.

What Is the Next Step in the Process for This ICR?

EPA will consider the comments received and amend the ICR as appropriate. The final ICR package will then be submitted to OMB for review and approval pursuant to 5 CFR 1320.12. At that time, EPA will issue another **Federal Register** notice pursuant to 5 CFR 1320.5(a)(1)(iv) to announce the submission of the ICR to OMB and the opportunity to submit additional comments to OMB. If you have any questions about this ICR or the approval process, please contact the technical person listed under **FOR FURTHER INFORMATION CONTACT**.

Dated: July 20, 2009.

James Hanlon,

Director, Office of Wastewater Management.

[FR Doc. E9–17927 Filed 7–27–09; 8:45 am]

BILLING CODE 6560–50–P

ENVIRONMENTAL PROTECTION AGENCY

[EPA–HQ–SFUND–2009–0265; FRL–8931–7]

RIN 2050–AG56

Identification of Priority Classes of Facilities for Development of CERCLA Section 108(b) Financial Responsibility Requirements

AGENCY: Environmental Protection Agency (EPA)

ACTION: Priority notice of action.

SUMMARY: Section 108(b) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended, establishes certain regulatory authorities concerning financial responsibility requirements. Specifically, the statutory language addresses the promulgation of regulations that require classes of facilities to establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances. CERCLA Section 108(b) also requires EPA to publish a notice of the classes for which financial responsibility requirements will be first developed. To fulfill this requirement, EPA is by this notice identifying classes of facilities within the hardrock mining industry for which the Agency will first develop financial responsibility requirements under CERCLA Section 108(b). For purposes of this notice, hardrock mining facilities include those which extract, beneficiate or process metals (*e.g.,* copper, gold, iron, lead, magnesium, molybdenum, silver, uranium, and zinc) and non-metallic, non-fuel minerals (*e.g.,* asbestos, gypsum, phosphate rock, and sulfur).

FOR FURTHER INFORMATION CONTACT: For more information on this notice, contact Ben Lesser, U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery, Mail Code 5302P, 1200 Pennsylvania Ave., NW., Washington, DC 20460; telephone (703) 308–0314; or (e-mail) *Lesser.Ben@epa.gov;* or Elaine Eby, U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery, Mail Code 5304P,1200 Pennsylvania Ave., NW., Washington, DC 20460; telephone (703) 603–844; or (e-mail) *Eby.Elaine@epa.gov.*

SUPPLEMENTARY INFORMATION:

A. How Can I Get Copies of This Document and Other Related Information?

This **Federal Register** notice and supporting documentation are available in a docket EPA has established for this action under Docket ID No. EPA–HQ–SFUND–2009–0265. All documents in the docket are listed on the *http://www.regulations.gov* Web site. Although listed in the index, some information may not be publicly available, because for example, it may be Confidential Business Information (CBI) or other information, the disclosure of which is restricted by statute. Certain material, such as copyrighted material, is not placed on the Internet and will be publicly available only in hard copy form. Publicly available docket materials are available either electronically through *http://www.regulations.gov* or in hard copy at the RCRA Docket, EPA/DC, EPA West, Room 3334, 1301 Constitution Avenue, NW., Washington, DC. The Docket Facility is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Public Reading Room is (202) 566–1744, and the telephone number for the Superfund Docket is (202) 566–0270. A reasonable fee may be charged for copying docket materials.

B. Table of Contents

I. Introduction

Section 108(b), 42 U.S.C. 9608 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, as amended, requires in specified circumstances that owners and operators of facilities establish evidence of financial responsibility. Specifically, it requires the promulgation of regulations that require classes of facilities to establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances. The section also instructs that the President: [1]

> * * * identify those classes for which requirements will be first developed and publish notice of such identification in the **Federal Register**.[2]

EPA is publishing this notice to fulfill its obligations under CERCLA Section 108(b) to identify those classes of facilities, owners, and operators (herein referred to as classes of facilities) for which financial responsibility requirements will first be developed.

For the reasons that follow, the Agency has identified classes of facilities within the hard-rock mining industry as its priority for the development of financial responsibility requirements under CERCLA Section 108(b). For purposes of this notice only, hardrock mining is defined as the extraction, beneficiation or processing of metals (*e.g.,* copper, gold, iron, lead, magnesium, molybdenum, silver, uranium, and zinc) and non-metallic, non-fuel minerals (*e.g.,* asbestos, gypsum, phosphate rock, and sulfur).[3] (*See* Section VI of this notice for a discussion of EPA's consideration of additional classes of facilities for developing financial responsibility requirements under Section 108(b) of CERCLA.)

II. EPA's Approach for Identifying Those Classes of Facilities for Which Requirements Will Be First Developed

In accordance with CERCLA Section 108(b) EPA worked to determine which classes of facilities it should identify as its priority. CERCLA Section 108(b) directs the President to ''identify those classes for which requirements will be first developed and publish notice of such identification [.]'' However, this simple sentence does not spell out a particular methodology by which the identification is to be made. While EPA views this statutory ambiguity as allowing substantial discretion in making the identification, EPA looked to the rest of CERCLA Section 108(b) to inform its exercise of this discretion.

Examination of CERCLA Section 108(b) as a whole reveals repeated references to the concept of ''risk.'' The first sentence of paragraph (b)(1) refers to ''requirements * * * that classes of facilities establish and maintain evidence of financial responsibility consistent with the *degree and duration of risk''* and the last sentence states that ''[p]riority in the development of such requirements shall be accorded to those classes of facilities * * * which the President determines present the *highest level of risk of injury.''* Paragraph (b)(2) also states that ''[t]he level of financial responsibility shall be initially established, and, when necessary, adjusted to *protect against the level of risk* which the President in his discretion believes is appropriate * * * .'' Accordingly, EPA chose to look for indicators of risk and its related effects to inform its selection of classes for which it would first develop requirements under CERCLA Section 108(b). As a practical method of doing so, EPA reviewed information contained in a number of studies, reports, and analyses. This review pointed to numerous factors EPA should consider. For example, typical elements in evaluating risk to human health and the environment include: the probability of release, exposure, and toxicity.[4] While some of the considerations reflect these basic elements of risk evaluation, others relate more closely to the severity of consequences that result when those risks are realized, such as the releases' duration if not prevented or quickly controlled as a result of economic factors and the exposures that can result. Therefore, EPA has chosen to evaluate the following factors: (1) Annual amounts of hazardous substances released to the environment; (2) the number of facilities in active operation and production; (3) the physical size of the operation; (4) the extent of environmental contamination; (5) the number of sites on the CERCLA site inventory (including both National Priority List (NPL) sites and non-NPL sites); (6) government expenditures; (7) projected clean-up expenditures; and (8) corporate structure and bankruptcy potential.

Toxicity is reflected in the designation of substances as CERCLA hazardous substances. Current releases of hazardous substances, number of operating facilities, the physical size of an operation, the extent of environmental contamination, and the number of sites on the CERCLA site inventory (non-NPL sites and NPL sites) are factors that can relate to the probability of a release of a hazardous substance, as well as the potential for exposure. These are discussed in detail, in Section IV of this notice. Government expenditures, projected clean-up costs, and corporate structure and bankruptcy potential can relate to the severity of the consequences as a result of releases and exposure of hazardous substances. These are discussed in Section V of this notice.

EPA's review of all these factors, as reflected in the information presented in this notice and included in the docket, makes it readily apparent that hardrock mining facilities present the type of risk that, in light of EPA's current assessment, justifies designating such facilities as those for which EPA will first develop financial responsibility requirements pursuant to CERCLA Section 108(b).[5]

III. Identification of Classes of Facilities in Hardrock Mining

For purposes of this notice, EPA has included the following classes of facilities under the general title of hardrock mining: facilities which extract, beneficiate or process metals (*e.g.* copper, gold, iron, lead, magnesium, molybdenum, silver, uranium, and zinc) and non-metallic, non-fuel minerals (*e.g.* asbestos, gypsum, phosphate rock, and sulfur).[6] As explained below, hardrock mining facilities share common characteristics, and are thus being identified as a group. At the same time, those facilities included in the definition above differ such that ''hardrock mining facilities'' are properly considered to encompass multiple ''classes'' of facilities. The various classes in this notice's definition of hardrock mining are involved in two general activities: (1) The extraction of an ore or mineral from the earth; and (2) using various beneficiation activities and processing operations to produce a targeted material product, such as a metal ingot. The operations that comprise hardrock mining (*i.e.,* extraction, beneficiation, and then processing) are all part of a sequential process of converting

[1] Executive Order 12580 delegates this responsibility to the Administrator of the U.S. Environmental Protection Agency (''EPA'' or ''the Agency'') for non-transportation related facilities. 52 FR 2923, 3 CFR, 1987 Comp., p. 193.

[2] 42 U.S.C. 9608 (b)(1).

[3] *See* memorandum to Jim Berlow, USEPA from Stephen Hoffman, USEPA and Shahid Mahmud, USEPA. *Re:* Mining Classes Not Included in Identified Classes of Hardrock Mining. June 2009.

[4] ''Risk Assessment in the Federal Government: Managing the Process.'' National Research Council. National Academy Press, Washington, DC. 1983.

[5] Today's identification of hardrock mining is not itself a rule, and does not create any binding duties or obligations on any party. Additional research, outreach to stakeholders, proposed regulations, review of public comments, and finalization of those regulations are needed before hardrock mining facilities are subject to any financial assurance requirements.

[6] EPA notes that this notice does not affect the current Bevill status of extraction, beneficiation and processing wastes as codified in 40 CFR 261.4(b)(7).

material removed from the earth into marketable products, even though the intermediate and end products differ. Extraction, beneficiation or processing of ores and minerals can involve similar processes across types of mining, as discussed below.

However, hardrock mining is also properly considered to encompass multiple ''classes'' that represent a range of activities and marketable products. Extraction differs from beneficiation and both differ from processing, and depending upon the product sought, different types of processes are used. Extraction, also called mining, is the removal of rock and other materials that contain the target ore and/or mineral. The physical processes used to accomplish this vary, but are nonetheless often shared across different types of mining. These physical processes include surface, underground, and in-situ solution mining. Overburden and waste rock are removed during surface and underground extraction processes in order to gain access to the ore. Overburden and waste rock are disposed of in dumps near the mine. The dumps may or may not be lined or covered. In-situ mining involves the recovery of the metal from the ore by circulating solutions through the ore in its undisturbed geologic state and recovering those solutions for processing. The principal environmental protection concern with in-situ mining is the control and containment of the leach solutions.

Typically the next step after extraction, beneficiation involves separating and concentrating the target mineral from the ore. There are, however, many different ways in which beneficiation can occur. Beneficiation activities generally do not change the mineral values themselves other than by reducing (*e.g.* crushing or grinding) or enlarging (pelletizing or briquetting) particle size to facilitate processing, but can involve the introduction of water, other substances, and chemicals (including hazardous substances). A common beneficiation technique is flotation. Froth flotation involves adding forced air and chemicals to an ore slurry causing the target mineral surfaces to become hydrophobic and attach to air bubbles that carry the target minerals to the top of a floatation vessel. The surface froth containing the concentrated mineral is removed, and thus separated from the other waste minerals. The remaining waste minerals are called tailings. Leaching, another beneficiation technique, involves the addition of chemicals to ores or flotation concentrates in order to dissolute the target metal. For example, solvents, such as sulfuric acid are used to leach copper and sodium cyanide is used to leach gold. Following leaching, the leftover waste product is called spent ore (in heap leaching) or tailings (in other types of leaching). There are various other beneficiation techniques and intermediate processes that are used and not described here. However, flotation and leaching are the most common techniques used in the mining industry. Tailings from beneficiation are disposed in a variety of ways, most commonly in tailing ponds. Design of tailings ponds differ and may or may not include liners, seepage control, surface water diversions, and final covers. Regardless, many tailings ponds require long-term management of waste and the impoundment dam.

Processing is the refining of ores or mineral concentrates after beneficiation to extract the target material. As with beneficiation, there are many different ways of processing the ores or mineral concentrates. For example, mineral processing operations can use pyrometallurgical techniques (the use of higher temperatures as in smelting), to produce a metal or high grade metallic mixture. Smelting generates a waste product called slag. Slag is initially placed directly on the ground to cool, and is often subsequently managed into a wide range of construction materials (*e.g.,* road bed or foundation bedding).

Both because of the ways that the facilities covered by this notice fit together, and because of the range of activities that they cover, EPA believes hardrock mining is properly identified as a group and considered to include multiple classes of facilities.

IV. Hardrock Mining—Releases and Exposure to Hazardous Substances

As discussed above, evaluations of risk typically include considerations of the probability of a release, including its potential scale and scope, the exposure potential and toxicity. EPA research indicates that the hardrock mining industry typically operates on a large scale, with releases to the environment and, in some situations, subsequent exposure of humans, organisms, and ecosystems to hazardous substances on a similarly large scale. Indeed, EPA estimates that the hardrock mining industry is responsible for polluting 3,400 miles of streams and 440,000 acres of land.[7] The U.S. Forest Service (USFS) estimates that approximately 10,000 miles of rivers and streams may have been contaminated by acid mine drainage from the metal mining industry.[8]

The Agency examined its 2007 Toxic Release Inventory (TRI), and this data revealed that the metal mining industry[9] (*e.g.,* gold ore mining, lead ore and zinc ore mining, and copper ore and nickel ore mining) releases enormous quantities of toxic chemicals, at nearly 1.15 billion pounds or approximately 28 percent of the total releases by U.S. industry that is required to report under the TRI program.[10][11] This overall percentage has remained relatively stable since 2003, ranging from 25 percent (1.07 billion pounds) of total releases in 2004 to 29 percent (1.26 billion pounds) of total releases in 2006. In 2007, the majority of releases of hazardous substances from the metal mining industry were to the land, with additional releases to both the air and surface waters. Additional releases of hazardous substances were reported to TRI from metal processing facilities (*e.g.,* primary smelting of copper) with significant releases to the air and land.

The potential for releases of and exposure to hazardous substances is also reflected in the number of active facilities operating in the U.S. While estimates of the number of active mining facilities vary, in 2004, EPA estimated that there were 1,000 metal and non-metal mineral mines and processing facilities in the U.S. Furthermore, many mining facilities have been in operation for decades and can exceed thousands of acres in size.[12] Since large mines may be operated for decades, this can extend the time frame for potential releases and exposure of hazardous substances. At individual facilities, hardrock mining operations

7 U.S. EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

8 U.S. EPA 2004. ''Nationwide Identification of Hardrock Mining Sites.'' Office of Inspector General. Report No. 2004–P–00005. Accessed at: *http://epa.gov/oig/reports/2004/20040331-2004-p-00005.pdf.*

9 Metal mining industry is defined as NAICS Code 2122 (Metal Mining).

10 U.S. EPA 2009. Toxic Release Inventory, 2007 Updated Data Releases, as of March 19, 2009.

11 TRI estimates include all on-site and off-site releases to the land, air and surface water, including those disposed of in RCRA Subtitle C hazardous waste land disposal units and Safe Drinking Water Act (SDWA) permitted underground injection (UIC) wells. However, less than one percent of hazardous substances are managed in this manner. Thus, the data demonstrates the enormous volume of hazardous chemical releases reported to TRI by the metal mining industry and is an indication of the high volume of hazardous substances it manages, and the industry's potential for posing health and environmental risk.

12 National Research Council. 2005. *Superfund and Mining Megasites: Lessons from the Coeur d'Alene River Basin.* The National Academies Press, Washington, DC. Accessed at: *http://www.nap.edu/catalog.php?record_id=11359.*

may disturb thousands of acres of land and impact watersheds including, to varying degrees, effects on groundwater, surface water, aquatic biota, aquatic and terrestrial vegetation, wetlands, wildlife, soils, air, cultural resources, and humans that use these resources recreationally or for subsistence.[13]

Hardrock mining facilities also generate an enormous volume of waste, which may increase the risk of releases of hazardous substances. Annually, hardrock mining facilities generate between one to two billion tons of mine waste.[14] This waste can take a variety of forms, including mine water, waste rock, overburden, tailings, slag, and flue dust and can contain significant quantities of hazardous substances. The 2007 TRI data demonstrate that hardrock mining facilities reported large releases of many hazardous substances, including ammonia, benzene, chlorine, hydrogen cyanide, hydrogen fluoride, toluene, and xylene, as well as heavy metals and their compounds (*e.g.,* antimony, arsenic, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, selenium, vanadium and zinc).[15] Similarly, the National Research Council (NRC) has indicated that hazardous substances of particular concern include heavy metals, ammonia, nitrates, and nitrites.[16]

These releases, in some cases, have lead to ground and surface water contamination from acid mine drainage and metal leachate, and air quality issues resulting from heavy metal-contaminated dust or emissions of gaseous metals from thermal processes.[17] Acid mine drainage is the formation and movement of acidic water which dissolves and transports metals into the environment. This acidic water forms through the chemical reaction of surface water (rainwater, snowmelt, pond water) and shallow subsurface water with rocks (*e.g.,* waste rock, tailings, mine walls) that contain sulfur-bearing minerals, resulting in the production of sulfuric acid. Metals can be leached from rocks that come in contact with the acid, a process that may be substantially enhanced by bacterial action.[18] The resulting acidic and metal-contaminated fluids may be acutely or chronically toxic and, when mixed with groundwater, surface water and soil, may have harmful effects on humans, fish, animals, and plants.[19] When acid mine drainage occurs, it is extremely difficult and often expensive to control and often requires long-term management measures.[20] Air, land and water contamination may also result when waste rock dumps, tailings disposal facilities and open pits are not maintained properly and there are releases of hazardous substances to the environment.[21] Additional risks can occur with the use of cyanide in gold mining operations, including the possible release of cyanide into soil, groundwater, and/or surface waters or catastrophic cyanide spills.[22] Contaminants of concern at uranium mines include radionuclides. Due to the volume of the hazardous substances generated and released and the potential for long-term management of acid mine drainage, the cause for concern is only heightened.

Other studies and EPA's analysis of NPL data also underscores the risk of hardrock mining facilities. The NPL is a list of national priorities among the known or threatened releases of hazardous substances, pollutants or contaminants throughout the U.S. The Hazard Ranking System (HRS), the scoring system EPA uses to assess the relative threat associated with a release from a site, is the primary method used to determine whether a site should be placed on the NPL.[23] The HRS takes into account the three elements of environmental and human health risk: (1) Probability of release; (2) exposure; and (3) toxicity. EPA generally will list sites with scores of 28.50 or above. The HRS is a proven tool for evaluating and prioritizing the releases that may pose threats to human health and the environment throughout the nation. In 2005, the NRC noted that at the largest mining sites, or mega sites (*i.e.,* those with projected cleanup costs exceeding $50 million), ''wastes* * * are dispersed over a large area and deposited in complex hydrogeochemical and ecologic systems that often include human communities and public natural resources.'' [24] For example, a molybdenum mine located near Questa, New Mexico, began operations in 1919 and some underground mining operations are still in operation today. The mine's operational capacity is reportedly 20,000 tons of ore processed at the facility per day, although it does not typically operate at capacity. The site stretches over approximately three square miles of land. Across this large area, operations include an underground mine, a milling facility, a nine-mile long tailings pipeline and a tailing disposal facility. There is also an open pit and waste rock dumps at the mine site, which were created during open-pit mining operations. Other problems at the site include subsidence areas with a surface depression from active underground operations.[25]

In 2004, EPA's Office of Inspector General (OIG) examined 156 hardrock mining sites that are part of the CERCLA site inventory and concluded that ecological and environmental risks are often substantial. For the 82 Non-NPL sites that were evaluated, 64 percent had a current high or medium ecological/environmental risk, while the percentage of sites that were found to have low risk was only 13%. Another 23% had an unknown level of risk.[26]

In support of this notice, EPA examined not only sites listed on the

[13] National Research Council. 1999. *Hardrock Mining on Federal Lands.* National Academies Press. Washington, DC.

[14] U.S. EPA 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[15] *See* Memorandum to the Record: Toxic Release Inventory (TRI) Releases from Hardrock Mining Operations. June 2009.

[16] National Research Council. 1999. Hardrock Mining on Federal Lands. National Academies Press. Washington, DC. Also, EPA conducted a preliminary review of the Records of Decisions (RODs) for a selected group mining NPL sites. These substances were found to be common contaminants at these sites. Accessed at *http://books.nap.edu/catalog.php?record_id=9682.*

[17] U.S EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[18] U.S. EPA. 1997. ''EPA's National Hardrock Mining Framework.'' Accessed at: *http://www.epa.gov/owm/frame.pdf.*

[19] U.S. EPA 2009. Accessed at: *http://www.epa.gov/nps/acid_mine.html.*

[20] The conventional approach to treating contaminated ground or surface water produced through acid drainage involves an expensive, multi-step process that pumps polluted water to a treatment facility, neutralizes the contaminants in the water, and turns these neutralized wastes into sludge for disposal. U.S. EPA. Profile of the Metal Mining Industry. September 1995. *See also:* Lind, Greg. 2007. Testimony to the Subcommittee on Energy and Mineral Resources of the Committee on Natural Resources, U.S. House of Representatives, One Hundred Tenth Congress. Serial No. 110–46.

[21] U.S. EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[22] U.S. EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[23] U.S. EPA. 2007. ''Introduction to the Hazard Ranking System (HRS).'' Accessed at: *http://www.epa.gov/superfund/programs/npl_hrs/hrsint.htm.*

[24] National Research Council. 2005. *Superfund and Mining Megasites: Lessons from the Coeur d'Alene River Basin.* The National Academies Press, Washington, DC. Accessed at: *http://www.nap.edu/catalog.php?record_id=11359.*

[25] USEPA Administrative Order on Consent for Molycorp RI/FS (2001). Molycorp is proposed for listing on the NPL. More information is at *http://www.epa.gov/region6/6sf/pdffiles/0600806.pdf.*

[26] U.S. EPA 2004. ''Nationwide Identification of Hardrock Mining Sites.'' Office of Inspector General. Report No. 2004–P–00005, Figure 4.2. Accessed at: *http://epa.gov/oig/reports/2004/20040331-2004-p-00005.pdf.*

NPL, but also sites proposed (including sites with Superfund alternative approach agreements in place) and deleted from the NPL.[27] As of April, 2009, approximately 90 hardrock mining sites have been listed on the NPL, and another 20 facilities have been proposed for inclusion on the list.[28]

V. Hardrock Mining—Severity of Consequences Resulting From Releases and Exposure to Hazardous Substances

The severity of the consequences impacting human health and the environment as a result of releases and exposure of hazardous substances is evident by analyzing a number of factors. Specifically, the past and estimated future costs associated with protecting public health and the environment through what is often extensive and long-term reclamation and remediation efforts, as well as corporate structure and bankruptcy potential. This information also plays a significant role in leading EPA to conclude that classes of facilities involved in hardrock mining should be the first for which financial assurance requirements are developed under CERCLA Section 108(b).

The severity of consequences posed by hardrock mining facilities is evident in the enormous costs associated with past and projected future actions necessary to protect public health and the environment, after releases from hardrock mining facilities occur. In other words, the documented expenditures reflect efforts to correct the realized risks from hardrock mining facilities. As noted earlier, these facilities release large quantities of hazardous substances, often over hundreds of square miles and, in some instances, have resulted in groundwater and surface water contamination that requires long-term management and treatment. Remediation of these hardrock mining facilities has therefore been historically costly. EPA's past experience with these sites leads it to conclude that hardrock mining facilities are likely to continue to present a substantial financial burden that could be met by financial responsibility requirements. These enormous expenditures have been documented in a United States Government Accountability Office (GAO) study, and EPA's own data confirm the large amounts of money spent by the Federal government alone. The GAO, in its report ''Current Government Expenditures to Cleanup Hard Rock Mining Sites,'' reported that in total, the Federal government spent at least $2.6 billion to remediate hardrock mine sites from 1998 to 2007. EPA spent the largest amount at $2.2 billion, with the USFS, the Office of Surface Mining, and the Bureau of Land Management spending $208 million, $198 million, and $50 million, respectively.[29] EPA's expenditure data show that between 1988 and 2007, for mining sites with response actions taken under EPA removal and remedial authorities (including sites proposed, listed, and deleted from the NPL and sites with Superfund alternative approach agreements in place), approximately $2.7 billion was spent.[30] [31] Of this total, $2.4 billion was spent at the 84 sites listed as final on the NPL list at that time.[32]

Estimated costs of remediation for all hardrock mining facilities from several sources have generally been in the range of billions of dollars. EPA has estimated that the cost of remediating all hardrock mining facilities is between $20 and $54 billion. EPA's analysis showed that if the total Federal, State, and potentially responsible party outlays for remediation were to continue at existing levels ($100 to $150 million annually), no more than eight to 20 percent of all cleanup work could be completed within 30 years.[33] In another analysis based on a survey of 154 large sites, EPA's OIG projected that the potential total hardrock mining remediation costs totaled $7 to $24 billion. OIG calculated that this amount is over 12 times EPA's total annual Superfund budget of about $1.2 billion from 1999 to 2004.[34] The annual Superfund budget from 2004 through 2008 remained consistent with OIG's assessment, at approximately $1.25 billion.[35] [36]

Common corporate structures and interrelated corporate failures within the hardrock mining industry increase the likelihood of uncontrolled releases of hazardous substances being left unmanaged, increasing risks. To begin with, mine ownership is typically complex, with individual mines often separately incorporated.[37] The existence of a parent-subsidiary relationship can present several risks. First, corporate structures may allow parent

[27] A significant number of response actions have been taken by several Federal agencies at hardrock mining facilities under CERCLA removal and emergency response authorities. Those actions were not evaluated for purposes of this Notice because of the lack of immediately available data. EPA alone took non-NPL removal actions at 99 mining sites between 1988 and October 2007. Provided to GAO for GAO 2008, ''Hardrock Mining: Information on Abandoned Mines and Value and Coverage of Financial Assurance on BLM Land.'' GAO–08–574T. Other Federal agencies also use non-NPL removal authorities to address releases from mining sites. Accessed at: *http://www.gao.gov/highlights/d08574thigh.pdf.*

[28] Provided to GAO for GAO 2008, ''Hardrock Mining: Information on Abandoned Mines and Value and Coverage of Financial Assurance on BLM Land.'' GAO–08–574T. Accessed at: *http://www.gao.gov/new.items/d08574t.pdf.* and updated to reflect sites finalized on the NPL in 2008 and 2009. The 2008 and 2009 NPL updates can be found at: *http://www.epa.gov/superfund/sites/npl/status.htm.*

[29] U.S. Government Accountability Office. 2008. ''Information on Abandoned Mines and Value and Coverage of Financial Assurance on BLM Land. GAO–08–574T. Accessed at: *http://www.gao.gov/highlights/d08574thigh.pdf.*

[30] Moreover, EPA's cost data likely underestimates true cleanup costs, because they do not include costs borne by the States and potentially responsible parties. These costs only reflect expenditures to date. To reach construction completion, many sites will require additional, substantial remediation efforts. In addition, sites with acid mine drainage may require water quality treatment in perpetuity. Lind, Greg. 2007. Testimony to the Subcommittee on Energy and Mineral Resources of the Committee on Natural Resources, U.S. House of Representatives, One Hundred Tenth Congress. Serial No. 110–46.

[31] U.S. EPA. 2007. Superfund eFacts Database. Accessed: October 24, 2007; U.S. Environmental Protection Agency. 2007 Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS). Provided to GAO for their report, GAO 2008, ''Hardrock Mining: Information on Abandoned Mines and Value and Coverage of Financial Assurance on BLM Land.'' GAO–08–574T. Accessed at: *http://www.gao.gov/highlights/d08574thigh.pdf.*

[32] U.S. EPA. 2007. Superfund eFacts Database. Accessed: October 24, 2007; U.S. Environmental Protection Agency. 2007 Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS). Provided to GAO for their report, GAO 2008, ''Hardrock Mining: Information on Abandoned Mines and Value and Coverage of Financial Assurance on BLM Land.'' GAO–08–574T, *http://www.gao.gov/new.items/d08574t.pdf.*

[33] U.S. EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[34] U.S. EPA 2004. ''Nationwide Identification of Hardrock Mining Sites.'' Office of Inspector General. Report No. 2004–P–00005. Accessed at: *http://epa.gov/oig/reports/2004/20040331-2004-p-00005.pdf.*

[35] Appropriation amounts reflect an average of the discretionary appropriation amounts in the President's Budget or Operating Plan between 2004 and 2008.

[36] No single source provides information on estimated future reclamation and remediation costs for hardrock mining facilities. In addition, for those estimates that do exist, remediation costs are often folded in with other reclamation activities, such as correcting safety hazards and landscaping, which leaves the amount attributable to remediation unknown. *See* U.S. EPA. 2004. ''Cleaning Up the Nation's Waste Sites: Markets and Technology Trends.'' EPA 542–R–04–015. Accessed at: *http://www.epa.gov/tio/pubisd.htm.*

[37] For example, one mining company's 2008 SEC 10–K filing noted that its segments included ''The Greens Creek unit, a 100%-owned joint venture arrangement, through our subsidiaries Hecla Alaska LLC, Hecla Greens Creek Mining Company and Hecla Juneau Mining Company. We acquired 70.3% of our ownership of Greens Creek in April 2008 from indirect subsidiaries of Rio Tinto, PLC.'' From this description, it appears that ownership of the mine has involved multiple subsidiaries, under both its current owner and under the previous ownership.

corporations to shield themselves from liabilities of their subsidiaries.[38] In a 2005 study, the GAO cited mining facilities as an example of businesses at risk of incurring substantial liability and transferring the most valuable assets to the parent that could not be reached for cleanup.[39]

Second, many mining interests are located outside of the U.S. According to one report, six of the top ten mining claim owners in the U.S. are multi-national corporations with headquarters outside the U.S.[40] Such multi-national corporations can be difficult to hold responsible for contamination in the U.S. because of the difficulties of locating and then obtaining jurisdiction over the ultimate parent company.

This is of particular concern since the hardrock mining industry has experienced a pattern of failed operations, which often require significant environmental responses that cannot be financed by industry.[41] The pattern of failed operations has been well documented. GAO investigated 48 hardrock mining operations on U.S. Department of Interior (DOI), Bureau of Land Management (BLM) Federal lands that had ceased operations and not been reclaimed by operators since BLM began requiring financial assurance under its regulations. Of the 48 operations, 30 cited bankruptcy as the reason for completing reclamation activities.[42] Numerous other examples exist of bankruptcies in the hardrock mining industry that resulted in or will likely require significant Federal responses, such as:

- When the owner/operator filed for bankruptcy in 1992, it left the Summitville mine in Colorado with serious cyanide contamination and acid mine drainage. In 1994, the site was listed on the NPL. In 2000, EPA estimated that the remediation cost at the mine would be $170 million.[43] As of October 2007, EPA had spent approximately $192 million in cleanup costs.[44]
- In 1999, another mining company filed for bankruptcy, leaving more than 100 million gallons of contaminated water and millions of cubic yards of waste rock at the Gilt Edge Mine in South Dakota.[45] EPA listed the site on the NPL in 2000 and estimated at that time the present value remediation costs to be $50.3 million.[46] Even this estimate, however, does not include water collection and treatment costs that will be handled under additional remediation plans. As of October 2007, EPA expenditures at this site exceeded $56.1 million.[47]
- In 1998, operators of the Zortman Landusky mine in Montana filed for bankruptcy. Numerous cyanide releases occurred during operations which have affected the community drinking water supply on a nearby Tribal reservation. Acid mine drainage has also permeated the ground and surface waters. The projected cleanup costs at the site are estimated to be approximately $85.2 million, of which only $57.8 million will be paid for by the responsible party. State and Federal authorities are projected to pay the remaining $27.4 million for cleanup.[48]
- A large mining company filed for bankruptcy in 2005. The company has estimated the total environmental claims filed against it to have been in excess of $5 billion. Recently approved settlements with the U.S. and certain State governments involving environmental clean-up claims, when combined with settlements already approved by the bankruptcy court for environmental clean-up claims, provide for allowed claims and payments in the bankruptcy in an amount in excess of $1.5 billion and involve in excess of 50 sites. EPA and DOI estimate their combined claims in the bankruptcy at the largest of these sites, an NPL site located in Idaho and Eastern Washington, to be in excess of $2 billion.[49]

Taking all this information into account, EPA concludes that classes of facilities within the hardrock mining industry are those for which EPA should first develop financial responsibility requirements under CERCLA Section 108(b), based upon those facilities' sheer size; the enormous quantities of waste and other materials exposed to the environment; the wide range of hazardous substances released to the environment; the number of active hardrock mining facilities; the extent of environmental contamination; the number of sites in the CERCLA site inventory, government expenditures, projected clean-up costs and corporate structure and bankruptcy potential.

VI. EPA's Consideration of Additional Classes of Facilities for Developing Financial Responsibility Requirements

The Agency believes classes of facilities outside of the hardrock mining industry also may warrant the development of financial responsibility requirements under CERCLA Section 108(b). Therefore, the Agency will continue to gather and analyze data on additional classes of facilities, beyond the hardrock mining industry, and will consider them for possible development of financial responsibility requirements. In determining whether to propose requirements under CERCLA Section 108(b) for such additional classes of facilities, EPA will consider the risks posed and, to do so, may take into account factors such as: (1) The amounts of hazardous substances released to the environment; (2) the toxicity of these substances; (3) the existence and proximity of potential receptors; (4) contamination historically found from facilities; (5) whether the causes of this contamination still exist; (6) experiences from Federal cleanup programs; (7) projected costs of Federal cleanup programs; and (8) corporate structures and bankruptcy potential. EPA also intends to consider whether financial responsibility requirements under CERCLA Section 108(b) will effectively reduce these risks. While the Agency recognizes that data for some of these factors may be unavailable or limited in

[38] *See U.S.* v. *Bestfoods,* 524 U.S. 51, 61 (1998) (''[i]t is a general principle of corporate law * * * that a parent corporation * * * is not liable for the acts of its subsidiaries.'')

[39] U.S. Government Accountability Office. 2005. ''Environmental Liabilities: EPA Should Do More to Ensure That Liable Parties Meet Their Cleanup Obligations.'' Report to Congressional Requesters. GAO–05–658, pp. 21–24. Accessed at: *http://www.gao.gov/highlights/d05658high.pdf.*

[40] Environmental Working Group. 2006. ''Who Owns the West?'' Accessed at: *http://www.ewg.org/mining/claims/index.php.*

[41] EPA notes that there are several potential explanations for these failures, such as a boom and bust cycle in the price of commodities, the finite life of a particular ore body or the possibility that closure or reclamation obligations exceed the remaining value of the operation, in addition to factors that can cause bankruptcies in other sectors. However, regardless of the cause, the fact remains a large number of bankruptcies and abandonments have occurred.

[42] U.S. Government Accountability Office. 2005. Hardrock Mining: BLM Needs to Better Manage Financial Assurances to Guarantee Coverage of Reclamation Costs. GAO–05–377. Accessed at: *http://gao.gov/products/GAO-05-377.*

[43] U.S. Environmental Protection Agency. 2000. *Liquid Assets 2000: America's Water Resources at a Turning Point.* EPA–840–B–00–001. Accessed at: *http://www.epa.gov/water/liquidassest.pdf.*

[44] U.S. Environmental Protection Agency. 2007. Superfund eFacts Database. Accessed: October 24, 2007.

[45] CDM. 2008. Final Feasibility Study Report for the Gilt Edge Superfund Site, Operable Unit 1 (OU1). Prepared for EPA, Region VIII. May 2008.

[46] U.S. EPA 2008. Record of Decision for the Gilt Edge Superfund Site Operable Unit 1 (OU1). Accessed at: *http://www.epa.gov/region8/superfund/sd/giltedge/RODGiltEdgeVolumeOne_Text.pdf.*

[47] U.S. EPA. 2007. Superfund eFacts Database. Accessed: October 24, 2007.

[48] U.S. Government Accountability Office. 2005. Hardrock Mining: BLM Needs to Better Manage Financial Assurances to Guarantee Coverage of Reclamation Costs. GAO–05–377. Accessed at: *http://gao.gov/products/GAO-05-377.*

[49] Asarco, LLC, *et al.* U.S. Bankruptcy Court Southern District of Texas. May 15, 2009, Case No. 05–21207, Docket No. 11343.

availability, it plans to consider whatever data are available.

As part of the Agency's evaluation, it plans to examine, at a minimum, the following classes of facilities: hazardous waste generators, hazardous waste recyclers, metal finishers, wood treatment facilities, and chemical manufacturers. This list may be revised as the Agency's evaluation proceeds. EPA is currently scheduled to complete and publish in the **Federal Register** a notice addressing additional classes of facilities the Agency plans to evaluate regarding financial responsibility requirements under CERCLA Section 108(b) by December 2009, and, at that time, will solicit public comment.

VII. Conclusion

Based upon the Agency's analysis and review, it concludes that hardrock mining facilities, as defined in this notice, are those classes of facilities for which EPA should identify and first develop requirements pursuant to CERCLA Section 108(b). EPA will carefully examine specific activities, processes, and/or metals and minerals in order to determine what proposed financial responsibility requirements may be appropriate. As part of this process, EPA will conduct a close examination and review of existing Federal and State authorities, policies, and practices that currently focus on hardrock mining activities.[50]

Dated: July 10, 2009.

Lisa P. Jackson,

Administrator.

[FR Doc. E9–16819 Filed 7–27–09; 8:45 am]

BILLING CODE 6560–50–P

ENVIRONMENTAL PROTECTION AGENCY

[FRL–8932–9]

Modification of the 1985 Clean Water Act Section 404(c) Final Determination for Bayou aux Carpes in Jefferson Parish, LA

AGENCY: Environmental Protection Agency (EPA).

ACTION: Notice.

SUMMARY: This is a notice of EPA's Modification of the 1985 Clean Water Act Section 404(c) Final Determination for Bayou aux Carpes to allow for the discharge of dredged or fill material for the purpose of the construction of the West Closure Complex as part of the larger flood protection project for the greater New Orleans area. EPA believes that this Final Determination for modification achieves a balance between the national interest in reducing overwhelming flood risks to the people and critical infrastructure of south Louisiana while minimizing any damage to the Bayou aux Carpes CWA Section 404(c) site to the maximum degree possible in order to avoid unacceptable adverse effects.

DATES: *Effective Date:* The effective date of the Final Determination for Modification was May 28, 2009.

ADDRESSES: U.S. Environmental Protection Agency, Office of Water, Wetlands Division, Mail code 4502T, 1200 Pennsylvania Ave, NW., Washington, DC 20460. The following documents used in the Bayou aux Carpes modification are listed on the EPA Wetlands Division Web site at *http://www.epa.gov/owow/wetlands/regs/404c.html:* New Orleans District of the Corps letter dated November 4, 2008, requesting that EPA modify the Bayou aux Carpes CWA Section 404(c) designation; Public Notice of Proposed Determination to modify the Bayou aux Carpes CWA Section 404(c) designation published in the **Federal Register** on January 14, 2009; April 2, 2009, Recommended Determination (RD) for modification of the Bayou aux Carpes 404(c) action; and the May 28, 2009, Modification of the 1985 Clean Water Act Section 404(c) Final Determination for Bayou aux Carpes. Additional documents that are related to the Bayou aux Carpes modification can be located on the U.S. Army Corps of Engineers New Orleans District Web site at *http://www.nolaenvironmental.gov/projects/usace_levee/IER.aspx?IERID=12.*

Publicly available document materials are available either electronically through *http://www.regulations.gov* or in hard copy at the Water Docket, EPA/DC, EPA West, Room 3334, 1301 Constitution Ave., NW., Washington, DC. The Public Reading Room is open from 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number for the Public Reading Room is (202) 566–1744, and the telephone number for the Water Docket is (202) 566–2426.

FOR FURTHER INFORMATION CONTACT: Mr. Clay Miller at (202) 566–1365 or by e-mail at *miller.clay@epa.gov.* Additional information and copies of EPA's Final Determination for Modification are available at *http://www.epa.gov/owow/wetlands/regs/404c.html* or *http://www.nolaenvironmental.gov/projects/usace_levee/IER.aspx?IERID=12.*

SUPPLEMENTARY INFORMATION: Section 404(c) of the Clean Water Act (CWA) (33 U.S.C. 1251 *et seq*) authorizes EPA to prohibit, restrict, or deny the specification of any defined area in waters of the United States (including wetlands) as a disposal site for the discharge of dredged or fill material whenever it determines, after notice and opportunity for public hearing, that such discharge into waters of the United States will have an unacceptable adverse effect on municipal water supplies, shellfish beds and fishery areas (including spawning and breeding areas), wildlife, or recreational areas.

Congress directed the U.S. Army Corps of Engineers (Corps) to enhance the existing Lake Pontchartrain and Vicinity Hurricane Protection project and the West Bank and Vicinity Hurricane Protection project to the 100-year level of protection. One section of this much larger project is within the Bayou aux Carpes area that is subject to a 1985 EPA CWA Section 404(c) action that prohibited the discharge of dredged or fill material in the Bayou aux Carpes site south of the New Orleans metro area. On November 4, 2008, the New Orleans District of the Corps requested a modification of the Bayou aux Carpes CWA Section 404(c) designation to accommodate discharges to the Bayou aux Carpes wetlands associated with the proposed enhanced levee system in Jefferson Parish, Louisiana.

In evaluating the Corps of Engineers proposal for modification of the 1985 Bayou aux Carpes CWA Section 404(c) Final Determination, the key elements of a Section 404(c) process were followed. These include a hearing and opportunity for the public to provide written comments, preparation and submittal of a Recommended Determination proposed by EPA Region 6 to EPA Headquarters, and a Final Determination for Modification issued by EPA Headquarters.

Background

On October 16, 1985, EPA issued a Final Determination pursuant to Section 404(c) of the Clean Water Act restricting the discharge of dredged or fill material in the Bayou aux Carpes site, Jefferson Parish, Louisiana, based on findings that the discharges of dredged or fill material into that site would have unacceptable

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[50] As part of developing proposed and final rules the Agency will consider whether hardrock mining facilities which have a RCRA Part B permit or are subject to interim status under RCRA Subtitle C and already are subject to RCRA financial assurance and facility-wide corrective action requirements need to also be subject to the financial responsibility requirements under Section 108(b) of CERCLA. In addition, EPA is aware and will consider in its development of proposed and final rules, that mining on Federal land triggers either the Bureau of Land Management's (BLM) Part 3809 regulations (43 CFR Part 3809) and the Forest Service's Part 228 regulations (36 CFR Part 228), both have financial responsibility requirements that cover reclamation costs. Many States also have reclamation laws.

WaterLegacy PTM Objections
Exhibit 3

EPA 910-R-14-001A | January 2014

EPA
United States
Environmental Protection
Agency

An Assessment of Potential Mining Impacts on Salmon Ecosystems of Bristol Bay, Alaska

Volume 1 – Main Report

Region 10, Seattle, WA
www.epa.gov/bristolbay

EPA 910-R-14-001A
January 2014

AN ASSESSMENT OF POTENTIAL MINING IMPACTS ON SALMON ECOSYSTEMS OF BRISTOL BAY, ALASKA

VOLUME 1—MAIN REPORT

U.S. Environmental Protection Agency
Region 10
Seattle, WA

Table 14-1. Probabilities and consequences of potential failures in the mine scenarios.

Failure Type	Probability[a]	Consequences
Tailings dam	4×10^{-4} to 4×10^{-6} per dam-year = recurrence frequency of 2,500 to 250,000 years[b]	More than 29 km of salmonid stream would be destroyed or degraded for decades.
Product concentrate pipeline	10^{-3} per km-year = 95% chance per pipeline in 25 years	Most failures would occur between stream or wetland crossing and might have little effect on fish.
Concentrate spill into a stream	1.5×10^{-2} per year = 1 stream-contaminating spill in 78 years	Fish and invertebrates would experience acute exposure to toxic water and chronic exposure to toxic sediment in a stream and potentially extending to Iliamna Lake.
Concentrate spill into a wetland	2.6×10^{-2} per year = 2 wetland-contaminating spills in 78 years	Invertebrates and potentially fish would experience acute exposure to toxic water and chronic exposure to toxic sediment in a pond or other wetland.
Return water pipeline spill	Same as product concentrate pipeline	Fish and invertebrates would experience acute exposure to toxic water if return water spilled to a stream or wetland.
Diesel pipeline spill	Same as product concentrate pipeline	Acute toxicity would reduce the abundance and diversity of invertebrates and possibly cause a fish kill if diesel spilled to a stream or wetland.
Culvert, operation	Low	Frequent inspections and regular maintenance would result in few impassable culverts, but for those few, blockage of migration could persist for a migration period, particularly for juvenile fish.
Culvert, post-operation	3×10^{-1} to ~6×10^{-1} per culvert; instantaneous = 11 to 22 culverts	In surveys of road culverts, 30 to 61% are impassable to fish at any one time. This would result in 11 to 22 salmonid streams blocked at any one time. In 10 to 19 of the 32 culverted streams with restricted upstream habitat, salmon spawning may fail or be reduced and the streams would likely not be able to support long-term populations of resident species.
Truck accidents	1.9×10^{-7} spills per mile of travel = 4 accidents in 25 years and 2 near-stream spills in 78 years	Accidents that spill processing chemicals into a stream or wetland could cause a fish kill. A spill of molybdenum concentrate may also be toxic.
Water collection and treatment, operation	0.93 = proportion of recent U.S. porphyry copper mines with reportable water collection and treatment failures	Water collection and treatment failures could result in exceedance of standards potentially including death of fish and invertebrates. However, these failures would not necessarily be as severe or extensive as estimated in the failure scenario, which would result in toxic effects from copper in more than 60 km of stream habitat.
Tailings storage facility spillway release	No data, but spills are known to occur and are sufficiently frequent to justify routine spillway construction	Spilled supernatant from the tailings storage facility could result in toxicity to invertebrates and fish avoidance for the duration of the event.
Water collection and treatment, managed post-closure	Somewhat higher than operation	Post-closure collection and treatment failures are very likely to result in release of untreated or incompletely treated leachates for days to months, but the water would be less toxic due to elimination of potentially acid-generating waste rock.
Water collection and treatment, after site abandonment	Certain, by definition	When water is no longer managed, untreated leachates would flow to the streams. However, the water may be less toxic.

[a] Because of differences in derivation, the probabilities are not directly comparable.

[b] Based on expected state safety requirements. Observed failure rates for earthen dams are higher (about 5×10^{-4} per year or a recurrence frequency of 2,000 years).

BOX 14-1. FAILURE PROBABILITIES

Table 14-1 presents probability estimates and consequences of different kinds of failures. Here, we explain the derivation of these estimates. As much as possible, multiple methods are used within a failure type to determine how robust the estimates may be. The methods differ among failure types and the results are not strictly equivalent, but they do convey the likelihood of occurrence. More details can be found in Chapters 8 through 11.

Tailings dam failure. The most straightforward method of estimating the annual probability of failure of a tailings dam is to use the failure rates of existing dams. Three reviews of earthen dam failures produced an average rate of 1 failure per 2,000 dam-years (i.e., a recurrence frequency of 2,000 years), or 5×10^{-4} per year. The argument against this approach is that it does not reflect current engineering practice. The State of Alaska's guidelines suggest that an applicant follow accepted industry design practices such as those provided by U.S. Army Corps of Engineers and the Federal Energy Regulatory Commission. Both regulatory agencies require a minimum factor of safety of 1.5 for the loading condition corresponding to steady seepage at the maximum storage facility. An assessment of the correlation of dam failure probabilities with safety factors against slope instability suggests an annual probability of failure of 1 in 1,000,000 years for Category I Facilities (those designed, built, and operated with state-of-the-practice engineering) and 1 in 10,000 years for Category II Facilities (those designed, built, and operated using standard engineering practice). This corresponds to risks of 10^{-4} to 10^{-6} per year. The advantage of this approach is that it addresses current regulatory expectations and engineering practices. The disadvantage is that we do not know whether standard practice or state-of-the-practice dams designed with safety factors would perform as expected. Slope instability is only one type of failure; other failure modes, such as overtopping during a flood, would increase overall failure rates. Slope stability failures account for about one-fourth of tailings dam failures, so the probability of failure from all causes could be estimated to be 1 in 250,000 (Category I) to 1 in 2,500 (Category II). The mine scenarios include up to three tailings storage facilities (TSFs), two with multiple dams, so the annual probability of any dam failing would be approximately equal to the annual probability of a single dam failure times the number of dams.

Pipeline failure. A review of observed pipeline failure rates for oil and gas pipelines yields an average annual probability of failure per kilometer of pipeline of 10^{-3} or a frequency of 1 failure per 1,000 km per year. This average risk comes very close to estimating the observed failure rate of the copper concentrate pipeline at the Minera Alumbrera mine, Argentina. This annual failure probability, over the 113-km length of each pipeline within the Kvichak River watershed, results in a 0.11 probability of a failure in each of the four pipelines each year, or a recurrence frequency of 8.5 years. If the probability of a failure is independent of location, and if it is assumed that spills within 100 m of a stream could flow to that stream, a spill would have a 0.14 probability of entering a stream within the Kvichak River watershed. This would result in an estimate of 0.015 stream-contaminating spills per year or 1 stream-contaminating spill over the duration of the Pebble 6.5 scenario (approximately 78 years). Similarly, a spill would have a 0.24 probability of entering a wetland, resulting in an estimate of 0.026 wetland-contaminating spills per year or 2 wetland-contaminating spills over the duration of the Pebble 6.5 scenario.

Water collection and treatment failure. During mine operation, collection or treatment of leachate from mine tailings, pit walls, or waste rock piles would be incomplete and could fail in various ways. In the routine operations scenario, leachate from the unlined TSFs and waste rock piles would not be fully collected. Equipment and operation failures and inadequate designs would also result in failures to avoid toxic emissions. Reviews of mine records found that 93% of operating porphyry copper mines in the United States reported a water collection or treatment failure (Earthworks 2012). Improved design and practices should result in lower failure rates, but given this record it is unlikely that failure rates would be lower than 10% over the life of a mine. During operation, failures should be brief (less than 1 week) unless they involve a faulty system design or parts that are difficult to replace. After a mine is abandoned (potentially many years after closure), water management would end and the discharge of untreated water would become inevitable but may not be problematic.

TSF spillway release. Releases of supernatant water from TSFs through spillways are unintended but are not uncommon (e.g., the release at Nixon Fork Mine described in Box 8-1). However, data on the frequency of such releases are unavailable. They are apparently sufficiently common that inclusion of a spillway in a tailings dam is a standard practice. Hence, it is judged likely that a release would occur over the 78-year life of the mine in the Pebble 6.5 scenario.

Culvert failure. Culvert failure is defined as a condition that blocks fish passage. Empirical data for culvert failures are not based on rates of failure of culverts but rather on instantaneous frequencies of culverts that were found to have failed in road surveys. The frequencies in recent surveys range from 0.30 to 0.61 (3 to 6×10^{-1}) per culvert. In the Kvichak River watershed, 35 streams that are believed to support salmonids (salmon, trout, or Dolly Varden) have culverts, so at any time 11 to 22 culverted streams would be expected to have blocked fish passage at the published frequencies. The proportion of failed culverts during mine operation should be much lower.

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August 31, 2017

SENT ELECTRONICALLY
MN Department of Natural Resources (NorthMetPermitting.DNR@state.mn.us)
ATTN: PolyMet NorthMet Project
500 Lafayette Road North
St. Paul, MN 55155-4045

RE: Comments on Draft PolyMet NorthMet Water Appropriation Permits
(2016-1363, 2016-1364, 2016-1365, 2016-1367, 2016-1369, 017-0260)

Dear Commissioner Landwehr,

The following comments are submitted on behalf of WaterLegacy, a Minnesota non-profit formed in 2009 to protect Minnesota's water resources and the communities who rely on them.

WaterLegacy believes proceeding with draft PolyMet water appropriation permits is premature and inconsistent with Minnesota law. None of the applicable documents – the draft permits released for public comment on August 11, 2017,[1] PolyMet's water appropriation permit applications,[2] or the PolyMet NorthMet final environmental impact statement (FEIS)[3] -- provide the protection of surface and groundwater required by Minnesota law.

The draft PolyMet water appropriation permits should be rejected on the following grounds:

1. The appropriations proposed in the draft PolyMet water appropriation permits far exceed those described in the PolyMet NorthMet FEIS, and their impacts on water resources have not been evaluated.
2. The draft PolyMet water appropriation permits do not assure an adequate supply of water resources. Minn. Stat. §103G.265, Subd. 1.
3. The draft PolyMet water appropriation permits do not ensure that groundwater use will be sustainable, will not harm ecosystems, or will protect surface water from negative impacts. Minn. Stat. §§103G.287, Subd. 3 and Subd. 5; 103G.285, Subd. 2. And Subd. 3.
4. The draft PolyMet water appropriation permits do not meet the requirements of Minnesota law for use of water for mining operations. Minn. Stat. §103G.297, Subd. 3.
5. The draft PolyMet water appropriation permits fail to comply with Minnesota law precluding consumptive use of more than 5,000,000 gallons per day of Lake Superior Basin waters unless specific conditions are met. Minn. Stat. §103G.265, Subd. 4.

[1] Draft PolyMet water appropriation permits 2016-1363, 2016-1364, 2016-1365, 2016-1367, 2016-1369, and 2017-0260, available online at http://www.dnr.state.mn.us/polymet/permitting/water_app.html
[2] PolyMet Water Appropriation Permit Applications, v.3 (Apr. 2017), p. 38, available online at http://files.dnr.state.mn.us/lands_minerals/northmet/water-approp/water-appropriation-permit-app-v3.pdf.
[3] PolyMet NorthMet FEIS (Nov. 2015) available online at http://www.dnr.state.mn.us/input/environmentalreview/polymet/feis-toc.html

6. The draft PolyMet water appropriation permits fail to demonstrate that PolyMet is capable of collecting 90 percent of contaminated groundwater as claimed.
7. The draft PolyMet water appropriations permits lack public accountability.
8. The draft PolyMet water appropriations permits fail to limit water use or the term of permits consistent with their stated purpose.

1. Water Use in Draft PolyMet Water Appropriations Permits Far Exceeds any Water Use Previously Analyzed.

The total appropriations proposed from the PolyMet Mine Site Area (Partridge River Headwaters) in the draft PolyMet water appropriation permits are more than an order of magnitude greater than the highest estimated water need described in the PolyMet NorthMet FEIS. Table 1 below illustrates the difference between Mine Site Area (Partridge River Headwaters) potential water appropriation described in the PolyMet NorthMet FEIS and water appropriations proposed in the draft PolyMet water appropriation permits.

Table 1 - Comparison of Mine Site Area (Partridge River Headwaters) Water Appropriations Draft PolyMet Water Appropriations Permits and Final Environmental Impact Statement

Draft Permit Number Description of Use	Draft PolyMet Water Appropriation Permit (gpm)	FEIS Highest Estimate (gpm)	FEIS (P90)
2016-1363			
East Pit Dewatering	2,340	1,750	5-146
2016-1364			
Central Pit Dewatering	1,300	55	5-146
2016-1365			
West Pit Dewatering	2,640	400	5-146
2016-1367			
Cat 1 containment construction	275		
Cat 1 containment operation	14,400	375	5-146
Cat 1 foundation construction	3,375		
Cat 2/3 foundation construction	1,525		
Cat 2/3 liner drainage	430	145	5-146
Cat 2/3 underdrain	50		
Cat 4 foundation construction	850		
Cat 4 liner drainage	130	0	5-146
Cat 4 underdrain	25		
Building construction	50		
EQ and construction water basin	75		
Mine water pond	200		
Misc. Construction	100	65	5-146
Ore surge foundation construction	200		
Ore surge liner drainage	80	25	5-146
Ore surge underdrain	25		
Stormwater pond construction	750		
All Mine Site Infrastructure	22,540		
TOTAL Mine Site Area Water	**28,820** gal/minute	**2,815** gal/minute	

There is no indication in this record that the Minnesota Department of Natural Resources (DNR) has evaluated the environmental impacts on surface water and groundwater of the proposed 28,820 gallons per minute appropriations from the Partridge River Headwaters watershed, an appropriation more than 10 times the water consumption described in the PolyMet NorthMet FEIS.

In addition, draft water appropriations from the proposed Plant Site Area (Embarrass River watershed and Second Creek) are more than double those described in the PolyMet NorthMet FEIS. Water appropriations from groundwater related to the Hydrometallurgical Residue Facility wick drain operations totaling 3,000 gallons per minute are proposed in the draft PolyMet water appropriation permits. The need, scope and impacts of such wick drain water appropriations were not discussed in the PolyMet NorthMet FEIS, other than the statement that water appropriations were "to be determined" in permitting.[4]

Table 2 below compares descriptions of Plant Site Area water appropriations in the FEIS and those reflected in draft PolyMet water appropriation permit 2016-1369.

Table 2 - Comparison of Plant Site Area (Second Creek & Embarrass River) Water Appropriations & Draft PolyMet Water Appropriations Permits and Final Environmental Impact Statement

Draft Permit Number Description of Use	Draft PolyMet Permit (gpm)	FEIS Estimate (gpm)	FEIS Citation
2016-1369			
Colby Lake pipe upgrade	300		
FTB seepage construction dewatering	3350		
FTB seepage capture (surface & groundwater)		2,697	5-52
Misc. construction dewatering	100		
Sewage construction dewatering	100		
Lined & concrete ponds	50		
Hydromet (HRF) wick drain pumping	2850	TBD	5-201
Hydromet (HRF) wick drain gravity	150	TBD	5-201
Hydromet (HRF) liner	250		
TOTAL Plant Site Area Water	**7,150**	**2,697**	

As explained in subsequent sections of these comments, Minnesota law requires that the commissioner assure an adequate supply of water resources, that the use of groundwater is sustainable and will not harm ecosystems, that groundwater appropriations be limited to prevent negative impacts on surface water, and that water only be used for mining if such use is necessary and will not impair the interests of the public in lands or waters.

Even if environmental review of the PolyMet NorthMet plan had reviewed these questions,[5] any conclusions so reached would not apply to Mine Site Area appropriations proposed in the draft PolyMet water appropriation permits, which are more than 10 times those in the FEIS or proposed Plan Site Area appropriations, which are more than double those previously reviewed.

[4] PolyMet NorthMet FEIS, 5-201.
[5] WaterLegacy' position is that the PolyMet NorthMet FEIS is inadequate to evaluate the adverse impacts of water appropriations as well as in other respects.

2. Draft PolyMet Water Appropriations Permits Do Not Assure an Adequate Supply of Water Resources.

Pursuant to Minnesota Statutes, the Commissioner of the Minnesota Department of Natural Resources (DNR) must assure an adequate supply of water when considering the issuance of water appropriations permits:

> The commissioner shall develop and manage water resources to assure an adequate supply to meet long-range seasonal requirements for domestic, municipal, industrial, agricultural, fish and wildlife, recreational, power, navigation, and quality control purposes from waters of the state. Minn. Stat. §103G.265, Subd. 1.

The draft PolyMet water appropriation permits would authorize total appropriations of 6.175 billion gallons per year of water for the PolyMet mine project. The draft permits would also authorize removal from the proposed Mine Site Area (Partridge River Headwaters) of 3.7 billion gallons of water per year.

Table 3 -Total Annual Water Appropriations Authorized by Draft PolyMet Water Appropriations Permits

Draft Permit Number Description of Use	Draft PolyMet Permit (million gallons per year)
2016-1363 (Mine Site Area)	
East Pit Dewatering	1,000
2016-1364 (Mine Site Area)	
Central Pit Dewatering	700
2016-1365 (Mine Site Area)	
West Pit Dewatering	800
2016-1367 (Mine Site Area)	
All Mine Site Infrastructure	1,200
2016-1369 (Plant Site Area)	
Mine Processing	675
2017-0260 (Colby Lake)	
Mine Processing	1,800
TOTAL Water Appropriation Authorized	**6,175 million gallons per year**

The use for which PolyMet's proposed consumption of waters in the Partridge River and Embarrass River watersheds in the Lake Superior Basin is intended is a relatively low priority for allocation of water under Minnesota law. Minn. Stat. §103G.261, Subd. 5. It cannot be assumed that such a low priority use should dominate a watershed or watersheds.

Under Minnesota law, prior to issuing the draft PolyMet water appropriation permits, the DNR must demonstrate it has assured an adequate supply of water in the Partridge River and Embarrass River watersheds as well as in Colby Lake, considering long-range and seasonal resources and requirements for fish and wildlife as well as for residential and municipal water use requirements. This assurance must be demonstrated, not merely alleged in a conclusory statement.

3. Draft PolyMet Water Appropriations Permits Do Not Ensure that Groundwater Use is Sustainable and Will Not Harm Ecosystems and Degrade Water.

Minnesota Statutes preclude issuance of water-use permits for appropriation from groundwater unless that appropriation is sustainable:

> The commissioner may issue water-use permits for appropriation from groundwater only if the commissioner determines that the groundwater use is sustainable to supply the needs of future generations and the proposed use will not harm ecosystems, degrade water, or reduce water levels beyond the reach of public water supply and private domestic wells constructed according to Minnesota Rules, chapter 4725. Minn. Stat. §103G.287, Subd. 5.

Minnesota law contemplates that the Commissioner will establish water appropriation limits where needed to protect groundwater resources. "When establishing water appropriation limits to protect groundwater resources, the commissioner must consider the sustainability of the groundwater resource, including the current and projected water levels, water quality, whether the use protects ecosystems, and the ability of future generations to meet their own needs." Minn. Stat. §103G.287, Subd. 3.

To comply with Minnesota law, PolyMet would need to demonstrate and the DNR would need to have a reasonable basis to determine that PolyMet's appropriations from the proposed Mine Site Area (permits 2016-1363, 2016-1364, 2016-1365 and 2016-1367) would be sustainable for future generations, would protect aquatic ecosystems and would not result in degradation of water in the upper Partridge River. This has not been done.

Although PolyMet has represented that changes in the average flows of the Partridge River, including those at the Mine Site Area (Partridge River Headwaters) shall be less than 10% during all stages of mine development,[6] PolyMet has not been required to demonstrate that this condition can actually be met.

In particular, PolyMet has not demonstrated, given actual precipitation and flow conditions, that the impacts of the proposed PolyMet Mine Site Area water appropriation permits authorizing 3.7 billion gallons of water removal each year from the Partridge River Headwaters would not reduce flows in the upper Partridge River by more than 10% at various times.

The draft PolyMet permits propose several new monitoring sites in the upper Partridge River. However, there is no disclosure in permitting documents of existing flows and predicted flows from monitoring at these and other upper Partridge River sites to demonstrate that upper Partridge River flow would not be reduced more than 10% due to PolyMet appropriations.[7]

In addition, neither the draft PolyMet permits nor the PolyMet permit applications identify the

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[6] *See* PolyMet NorthMet FEIS, 5-139; PolyMet Water Appropriation Permit Applications, v.3 (Apr. 2017), p. 38.

[7] New monitoring sites SW430, SW431 and SW 432 are identified PolyMet Water Appropriation Permit Applications, v.3 (Apr. 2017) Large Table 3, autop. 180 and in documents attached to draft permits 2016-1363, 2016-1364, 2016-1365 and 2016-1367. However, no justification is provided why monitoring isn't also required at SW413 as identified in the PolyMet applications Large Figure 11, autop. or why continuous monitoring by PolyMet is not being required at the Partridge River upstream of the confluence with Stubble Creek.

"protective elevation" for the upper Partridge River or low flow periods when consumptive appropriations may not be made. Minnesota law provides that groundwater appropriations that will have negative impacts to surface waters are subject to provisions in Section 103G.285 that protect surface water. Minn. Stat. § 103G.287, Subd. 2.

Minnesota Statutes Section 103G.285, which protects surface waters, requires that the DNR "shall set a protective elevation for the water basin, below which an appropriation is not allowed." Minn. Stat. § 103G.285, Subd. 3(b). That "protective elevation" must be based on the aquatic vegetation characteristics related to fish and wildlife habitat and the total volume of water within the basin, as well as existing uses of water. *Id*.

Section 103G.285 also provides that, if data are available, consumptive appropriations may not be made "during periods of specified low flows." Minn. Stat. §103G.285, Subd. 1. Were PolyMet or the DNR to state that data were not available to determine periods of low flows, such a claim would call into question the adequacy of the PolyMet NorthMet FEIS.

The DNR must set a protective elevation for the upper Partridge River that cannot be reduced by PolyMet appropriations and define the periods of low flow in the upper Partridge River during which PolyMet's appropriations from the proposed Mine Site Area must be prohibited. The DNR has completed neither critical task.

PolyMet draft water appropriations permits pertaining to the Plant Site Area, as well as those for the proposed Mine Site Area, fail to comply with Minnesota law requiring that the sustainability of appropriations, the protection of water quality and the protection of ecosystems must be demonstrated before water appropriations permits can be issued. Minn. Stat. §103G.287, Subd. 3 and Subd. 5.

Although the text of draft permit 2016-1369 states that PolyMet shall augment streamflow in Trimble Creek, Unnamed Creek, Second Creek and Unnamed (Mud Lake) creek to maintain the "mean annual streamflow" in each stream within ±20% of existing conditions, the draft permit admits that there has been no hydrologic model or demonstration by PolyMet that this condition can be met.

The draft permit states "Adaptive management shall be required if monitoring results show that streamflow cannot be maintained within ±20% of average annual tributary streamflow." The draft permit then states that DNR will review data collected ***after*** the water appropriations permits have been issued to "determine if a hydrologic model needs to be created," for the Embarrass River.

DNR's proposal that developing a hydrologic model and using actual monitoring data to determine whether PolyMet can meet permit conditions limiting streamflow changes in the Embarrass River watershed can be postponed until long after permits are issued and massive quantities of waters consumed fails to protect sustainable water resources. It is also contrary to Minnesota law.

4. Draft PolyMet Water Appropriation Permits Do Not Comply with Requirements of Minnesota Law Pertaining to Water Use for Mining Purposes.

Minnesota law precludes the grant of a permit for the use of waters for copper, nickel or copper-nickel mining unless the proposed use of waters is necessary for the mining and will not substantially impair the interests and benefits of the public in lands or waters. Minn. Stat. §103G.297, Subd. 3(1) and (2). As discussed in the preceding sections, the DNR has not evaluated the quantity of water proposed to be appropriated in environmental review (Section 1), has not determined whether the draft permits would assure an adequate water supply (Section 2), has neither set a protective level nor protected low flows for the upper Partridge River (Section 3) and has not determined that streamflow permit conditions for the Embarrass River watershed are realistic or based on any hydrologic model (Section 3). On this record, the commissioner has an insufficient basis to determine that the draft PolyMet water appropriation permits would not substantially impair the interests and benefits of the public in waters of the upper Partridge River and Embarrass River watersheds.

In addition, the permitting record does not support a determination that the proposed magnitude of water appropriations at either the Mine Site Area or the Plant Site Area are necessary for the mining of copper and nickel ores. At the proposed Mine Site Area, potential treatment of water appropriated through mine dewatering or other mine site activities and immediate return of water to the watershed could reduce water use affecting the Partridge River Headwaters.

At the proposed Plant Site, appropriations of 3,000 gallons per minute related to wick drains at the Hydrometallurgical Residue Facility appear to be required as a remediation measure due to the inadequacy of the foundation where PolyMet has proposed to locate the facility. A consulting expert report prepared for the DNR in May 2017 stated, "The soft ground beneath the proposed residue facility consists of up to 30 feet of slimes, peat and tailings concentrate. This will not be an adequate foundation for the 80 foot high basin."[8] The DNR consultants' review did not consider alternative locations for the Hydrometallurgical Residue Facility that might avoid the need for wick drains or otherwise conserve water resources. Until such alternative locations for the Hydrometallurgical Residue Facility are evaluated, the DNR cannot determine whether the level of Plant Site Area appropriations is in fact *necessary* as the law requires.

5. Draft PolyMet Water Appropriations Permits Fail to Comply with Minnesota Law Limiting Consumptive Use Exceeding 5,000,000 Gallons per Day.

Minnesota law precludes consumptive use of Great Lakes public waters exceeding 5,000,000 gallons per day average in any 30-day period unless the commissioner has notified and solicited comments on the proposed diversion or consumptive use from the offices of the governors of the Great Lakes states and premiers of the Great Lakes provinces, the appropriate water management agencies of the Great Lakes states and provinces, and the international joint commission and the consumption has also been approved by the legislature. Minn. Stat. §103G.265, Subd. 4. The draft PolyMet water appropriation permits reflect consumptive use of waters of the Lake Superior Basin. Minn. Stat. § 103G.005, Subd. 8.

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[8] Dick Van Zyl, Steve Gale, Cecilio Olivier, Stuart Grubb, *PolyMet Dam Safety Permit Application Review* (May 15, 2017), p. 6. This review memo, without its attachments, is enclosed with these comments.

Neither the draft PolyMet water appropriations permits nor PolyMet's most recent water appropriation permit applications disclose whether the combined PolyMet permits would exceed the 5,000,000 gallons per day average in a 30-day period -- the threshold provided in Minnesota law.

However, an illustration of estimated consumptive use in PolyMet's most recent water appropriations permit application suggests that it is likely that the 5,000,000-gallon per day average threshold would be exceeded. This illustration (Figure 8-1)[9] shows the temporal overlap of appropriations from various PolyMet water appropriation permits during mine operations. In this illustration, it appears that appropriations from PolyMet's permits aggregated together would exceed 5,000,000 gallons per day during various mine years.

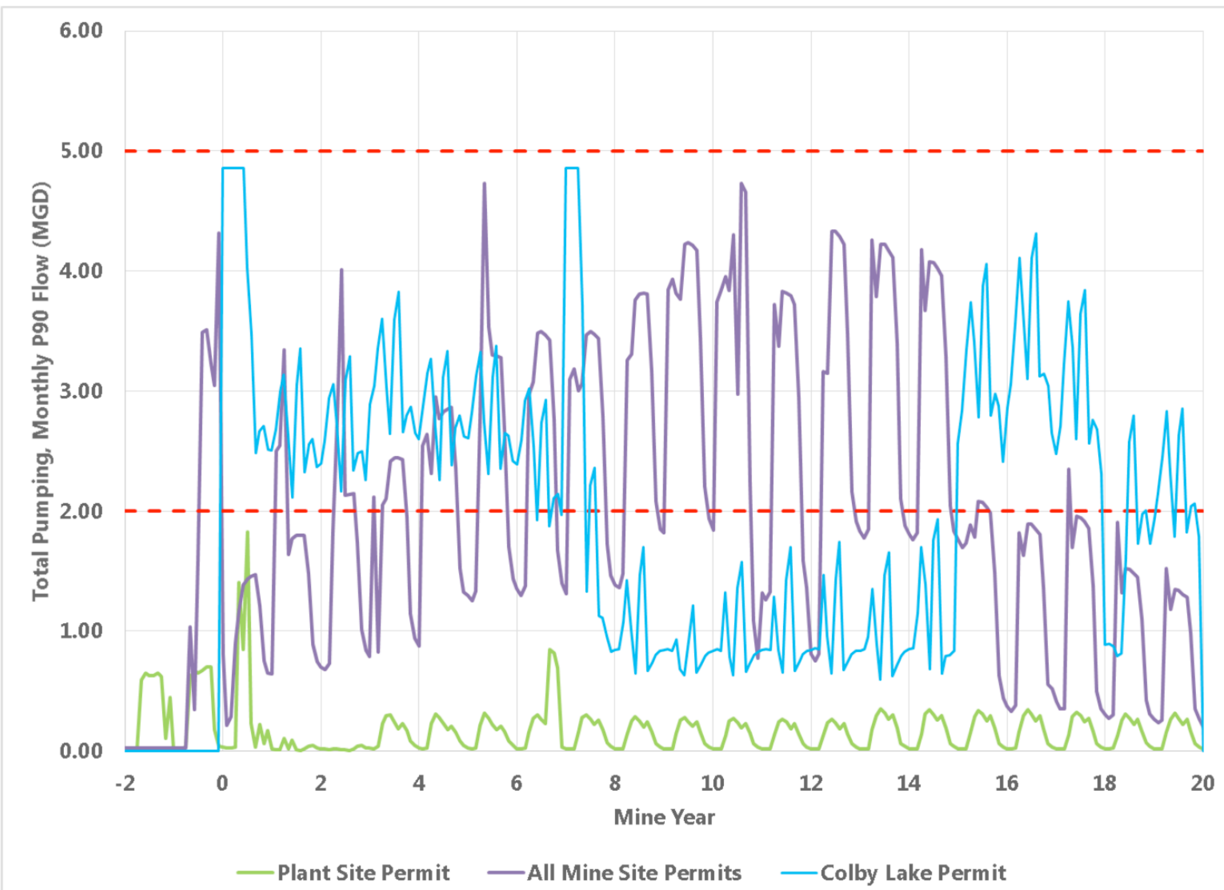


Figure 8-1 Monthly Total Pumping

Since PolyMet's most recent water appropriations permit applications were filed in April, proposed appropriations have increased 17 percent as illustrated in Table 4 below. As a result, the draft PolyMet water appropriations permits would authorize *56.7 million gallons per day* of water usage.

[9] PolyMet Water Appropriation Permit Applications, v. 3 (Apr. 14, 2017), Figure 8-1, p. 46.

Table 4 - Comparison of Appropriations in PolyMet Applications (Apr. 2017) and Draft PolyMet Water Appropriations Permits				
Draft Permit Number	**Draft PolyMet Permits**		**PolyMet Permit Applications**	
Description of Use	gal/minute	million gal/day	gal/minute	million gal/day
2016-1363 East Pit Dewatering	2340	3.370	2,340	3.370
2016-1364 Central Pit Dewatering	1300	1.872	1,300	1.872
2016-1365 West Pit Dewatering	2640	3.802	2,640	3.802
2016-1367 All Mine Site Infrastructure	22540	32.460	20,250	29.160
2016-1369 Mine Processing	7160	10.310	3,750	5.400
2017-0260 Mine Processing	3,400	4.896	3,400	4.896
TOTAL Water Appropriations	**39,380** gal/min	**56.7** mil. gal/day	**33,680** gal/min	**48.5** mil. gal/day

PolyMet's allowable water usage under its draft water appropriation permits is more than ten times the threshold of 5 million gallons per day set in Minnesota law. Minn. Stat. §103G.265, Subd. 4.

Thus, it is incumbent on the DNR to demonstrate that, at no time in future decades of operations or reclamation would PolyMet's water appropriations exceed the limit set in law to protect the Lake Superior Basin. If the DNR cannot provide such assurance, the commissioner must notify and solicit comments from governors and premiers or Great Lakes states and provinces, consider those comments, and secure legislative approval of the proposed consumptive use before granting PolyMet's water appropriations permits.

6. Draft PolyMet Water Appropriation Permits Fail to Demonstrate that PolyMet is Capable of Collecting 90 Percent of Contaminated Groundwater as Claimed.

PolyMet has repeatedly represented that the collection systems planned for both the NorthMet Plant Site tailings basin and at the Mine Site Category 1 waste rock stockpile will achieve collection of at least 90 percent of the groundwater seepage at these permanent facilities.[10] This representation was also repeated in the DNR Water Appropriation Permit fact sheet released to the public on August 11, 2017 with the PolyMet draft water appropriation permits, as follows:

> The proposed NorthMet project would not have a substantial effect on water quantity or stream flow . . . PolyMet would install and operate a system to capture at least 90 percent of the groundwater seepage at the tailings basin and the permanent waste rock stockpile at the Mine Site.[11]

[10] See e.g., PolyMet NorthMet FEIS, 5-52 Table 5.2.2-12, 5-181.

[11] DNR, NorthMet Mining Project Permitting, Water Appropriation Permit Fact Sheet (Aug. 11, 2017), p. 2 available online at http://files.dnr.state.mn.us/lands_minerals/northmet/water-approp/water-appropriation-draft-permit-fact-sheet.pdf.

It appears that the DNR has relied on this representation in proposing the draft PolyMet water appropriation permits and in asserting that the NorthMet project would not have a substantial adverse effect on water quality and stream flow.

However, neither the PolyMet NorthMet FEIS nor PolyMet's water appropriation permit applications provide any evidence based on actual performance of similar systems under similar conditions anywhere in the world that the collection of at least 90 percent of groundwater seepage is feasible, let alone likely. In addition, PolyMet draft water appropriation permit conditions neither require continuous and demonstrated compliance with PolyMet's promised 90 percent seepage collection rate nor provide any means to provide appropriate monitoring, disclosure and public accountability if PolyMet were to (predictably) fail to achieve anything approaching a 90 percent seepage collection rate from the unlined tailings basin and Category 1 waste rock stockpile.

In connection with collection of contaminated seepage, as with water appropriations of unexamined magnitude, issuance of the draft PolyMet water appropriation permits would allow a massive and uncontrolled experiment, rather than the careful determinations before permit issuance needed to comply with law and protect Minnesota waters.

7. The draft PolyMet water appropriations permits lack public accountability.

The proposed monitoring plan in the draft PolyMet water appropriation permits exacerbates WaterLegacy's concerns that water appropriations would be authorized that conflict with applicable Minnesota laws and fail to protect waters of the Lake Superior Basin in the Partridge River Headwaters, Embarrass River watershed and Second Creek. The DNR proposes in the draft PolyMet permits that monitoring results would only reported be annually, rather than monthly, and no results would be posted for public access and review. If such a discontinuous and secretive monitoring plan were to be adopted, seasonal stream impacts, massive groundwater seepage contamination and/or exceedance of the 5,000,000 gallon per day average water use would all be concealed from public accountability.

The draft PolyMet water appropriation permits further undermine PolyMet's potential to be held accountable by denying the public notice and an opportunity to comment prior to any proposed transfer or assignment of permits and prior to the DNR's potential future decisions to modify permit conditions. In addition to requiring that PolyMet demonstrate its ability to prevent harm to Minnesota water resources prior to permit issuance, the DNR must require permit conditions and provide public notice to ensure that PolyMet does not cut corners and adversely impact water resources.

8. The draft PolyMet water appropriations permits fail to limit water use or the term of permits consistent with their stated purpose.

The most valuable resource in Minnesota's Lake Superior Basin is not copper or nickel. It is the fresh water that that sustains plants, fish, wildlife and human communities.

The draft PolyMet water appropriations permits would relinquish this water resources to the foreign shell corporation, PolyMet Mining, Inc. without explicitly limiting the use of Minnesota waters to the purpose for which they are ostensibly being exploited, the purpose of mining and processing of copper, nickel and/or platinum group metals, and without providing that all permits must terminate if that specific use is not continuously maintained.

These draft PolyMet permits, thus, would allow a foreign corporation the indefinite right to appropriate 6.175 billion gallons per year of water from Minnesota's Lake Superior Basin. Such a transfer of public rights in public waters is neither consistent with Minnesota law nor consistent with the public interests and public benefits of future generations.

Conclusion

As detailed in these comments, WaterLegacy believes that proceeding with draft PolyMet water appropriation permits is premature and inconsistent with Minnesota law. The DNR must first conduct an analysis of the impacts on water supply, groundwater, surface water and use of Great Lakes waters based on the appropriations proposed in the draft PolyMet permits, which far exceed appropriations previously described in the NorthMet FEIS. The DNR must also set conditions to protect upper Partridge River elevation, average and low flows. Then the DNR must require PolyMet to demonstrate that it can and will comply with conditions to protect the Partridge River Headwaters, the streamflow conditions proposed to maintain Embarrass River creeks and Second Creek within ±20% of existing flows, and with PolyMet's promised 90% rate of contaminated groundwater seepage collection at the NorthMet tailings basin and Category 1 waste rock stockpile.

The DNR must further analyze whether the magnitude of PolyMet's water appropriations are in fact "necessary" or are only preferred by PolyMet in order to externalize its costs to the greatest extent possible. Finally, before deciding whether to grant PolyMet water appropriation permits, the DNR must determine what permit conditions, monitoring and reporting requirements, public review mechanisms and permit term limits could be sufficient to ensure that PolyMet, even if it has the capacity to meet conditions that protect Minnesota water resources, will in fact choose to do so during operations, reclamation and long-term closure.

WaterLegacy opposes issuance of the draft PolyMet water appropriations permits noticed for public review and believes that they should be rejected. Minnesota law requires additional analysis and protections before any PolyMet water appropriation permits could be granted.

Sincerely yours,

Paula G Maccabe

Paula Goodman Maccabee
Counsel/Advocacy Director for WaterLegacy

cc: Minnesota Pollution Control Agency
U.S. Army Corps of Engineers
U.S. Forest Service
U.S. Environmental Protection Agency
Fond du Lac, Grand Portage and Bois Forte Bands of the Lake Superior Chippewa

Enclosure

POLYMET
MINING

NorthMet Project

Flotation Tailings Management Plan

Version 7

Issue Date: May 15, 2017

This document was prepared for Poly Met Mining, Inc.
by Barr Engineering Co.

Attachment B

Saint Anthony Falls Tailings Deposition Modeling Report (previously submitted)

Physical Model Study of Fine-Grained Tailings Delta Formation under Various Inflow Conditions: Project Report

Project Report Number 551

Prepared by

St. Anthony Falls Laboratory
University of Minnesota

For

Barr Engineering Company

March 2011

Table 1 – Slurry Source Information

Item	Qty	Unit
Solids Production*	1452	tons/hour
Tailings Production (wt)	34848	tons/day
Tailings Production (wt)	806.7	lb/sec
Liquor Flow*	3161	tons/hour
Liquor Flow	75864	tons/day
Liquor Flow	1756.1	lb/sec
Slurry Flow*	4614	tons/hour
Slurry Flow	110736	tons/day
Slurry Flow	2563.3	lb/sec
Solids Fraction by wt in slurry*	31.5	% wt
Specific Gravity of Solids*	3	
Specific Weight of Solids	187.2	lb/ft^3
Specific Gravity of Slurry*	1.322	
Specific Weight of Slurry	82.5	lb/ft^3
Tailings (Solids) Production (volume)	4.3	ft^3/sec
Water Flow Rate (volume)	28.1	ft^3/sec
Volumetric Flow Rate for Slurry	31.1	ft^3/sec
Volumetric Flow Rate for Slurry*	13947	gal/min
Solids Fraction by Volume	13.90%	% vol

* Value provided by Barr Engineering.

Independent Expert Engineering Investigation and Review Panel

Report on Mount Polley Tailings Storage Facility Breach

January 30, 2015

Report on Mount Polley Tailings Storage Facility Breach

Independent Expert Engineering Investigation and Review Panel

TABLE OF CONTENTS

TABLE OF CONTENTS *continued*

EXECUTIVE SUMMARY

THE EMBANKMENTS

Three contiguous embankments confine the Mount Polley tailings storage facility (TSF). Of these, the Perimeter Embankment, where the breach occurred, was the northern flank of the TSF.

The embankments are composed of a core with the function of acting as an impervious element. Downstream of the core, a filter zone restrains material in the core from outward migration. The core and filter are then supported by a rockfill zone. In the upstream direction, the core is supported by an upstream fill zone composed of rockfill and/or tailings.

THE BREACH

The breach occurred within the Perimeter Embankment. At the time of the breach, the TSF was permitted under the Ministry of Energy and Mines, Permit M-200, with approval to raise the crest by 2.5 metres. The breach occurred early on August 4, 2014 at a crest elevation 1 metre short of its permitted elevation. Loss of containment was sudden, with no warning. The recorded pond elevation at 6:30 pm on August 3, 2014 was 2.3 metres below the crest.

THE MANDATE

Following the breach of the tailings storage facility at the Mount Polley Mine, the Government of British Columbia, through the Ministry of Energy and Mines, together with the Williams Lake Indian Band and the Soda Creek Indian Band, established an independent expert investigation and review panel (the Panel) to investigate and report on that breach. The Panel was required to submit a final report to the Ministry of Energy and Mines and the Williams Lake Indian Band and the Soda Creek Indian Band on or before January 31, 2015.

The purpose of the investigation has been as follows:

- To investigate and report on the cause of the failure of the tailings storage facility that occurred on August 4, 2014 at the Mount Polley Mine (the Mine) in B.C.
- In addition, the Panel may make recommendations to government on actions that could be taken to ensure that a similar failure does not occur at other mine sites in B.C.
- The Panel is authorized, as part of its investigations and report, to comment on what actions could have been taken to prevent this failure and to identify practices or successes in other jurisdictions that could be considered for implementation in B.C.

EXECUTIVE SUMMARY

Further, it was expected that the Panel would:

- Identify any mechanism(s) of failure of the tailings storage facility.
- Identify any technical, management or other practices that may have enabled or contributed to the mechanism(s) of failure. This may include an independent review of the design, construction, operation, maintenance, surveillance and regulation of the tailings storage facility.
- Identify any changes that could be considered to reduce the potential for future such occurrences.

PANEL ACTIVITIES

The Panel began its inquiry with multiple hypotheses for failure:

- Human intervention
- Overtopping
- Piping and cracking
- Foundation failure

The Panel found no evidence of failure due to either human intervention or failure due to overtopping, notwithstanding the fact that an episode of overtopping over portions of the Perimeter Embankment occurred in May 2014. The question of piping and cracking, which is a common cause of failure of earth dams, received corresponding attention. Although factors of concern were identified by the Panel, it did not find evidence that piping and/or cracking caused the breach.

This reduced the focus of the Panel to failure in the foundation of the embankment. Visual evidence of bodily outward displacement and rotation of the embankment remnants were consistent with foundation failure. A foundation can be weak and fail in a number of ways. One is the presence of a weak layer that had been undetected during design. Another is the presence of a brittle stratum that loses strength as it comes under load and becomes too weak to support the load applied by the embankment and TSF contents, so that failure ensues. Yet another possibility is the presence of a layer that is compressible under the applied load and, when stressed, develops high pore pressure that results in weakening of an otherwise much stronger material. This is termed undrained failure. It was the object of the site studies undertaken by the Panel to determine which of these foundation failure mechanisms prevailed.

EXECUTIVE SUMMARY

The Panel undertook comprehensive Surface Investigations that provided detailed, observable information on the sliding mechanism that had occurred. A challenging and complex Subsurface Investigation was also undertaken, partly in collaboration with the site investigation program initiated by the both the Mines Inspector and Mount Polley Mining Corporation (MPMC), and in addition, by the Panel alone.

The Subsurface Investigation was particularly valuable in defining the controlling stratigraphy in the breach area and identifying that the failure occurred in a glaciolacustrine layer, called Upper GLU. No indication of pre-shearing or the presence of markedly strain-weakening materials was detected, leaving undrained failure in the Upper GLU as the only viable hypothesis. The type and extent of pre-failure site investigations were not sufficient to detect this stratum or to identify its critical nature. The Panel's Subsurface Investigation was structured to obtain undisrupted samples of the Upper GLU and subsequently determine its properties.

The Upper GLU was found to be preconsolidated prior to embankment construction, but became normally consolidated under the loads applied by construction of the Perimeter Embankment. That is, it had experienced prior consolidation and strengthening under loads in its geological past, but not under the loads associated with the Perimeter Embankment, which created the normally consolidated state. Under these conditions, the Upper GLU was compressible and susceptible to undrained failure. This condition had not been recognized in the design of the TSF.

Laboratory tests were performed to determine the undrained strength of the Upper GLU and these parameters were utilized in computer analyses to calculate whether failure should have occurred under the applied load. The results were confirmatory.

EXECUTIVE SUMMARY

CONCLUSIONS

The Panel concluded that the dominant contribution to the failure resides in the design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous GLU layer in the vicinity of the breach and to recognize that it was susceptible to undrained failure when subject to the stresses associated with the embankment.

The specifics of the failure were triggered by the construction of the downstream rockfill zone at a steep slope of 1.3 horizontal to 1.0 vertical. Had the downstream slope in recent years been flattened to 2.0 horizontal to 1.0 vertical, as proposed in the original design, failure would have been avoided. The slope was on the way to being flattened to meet its ultimate design criteria at the time of the incident.

REGULATORY OVERSIGHT

The Panel reviewed the roles and responsibilities of the B.C. Ministry of Energy and Mines (the Regulator) and its interactions related to the MPMC TSF. The Panel found that inspections of the TSF would not have prevented failure and that the regulatory staff are well qualified to perform their responsibilities. The Panel found that the performance of the Regulator was as expected.

THE FUTURE

The Panel has examined the historical risk profile of the current portfolio of tailings dams in B.C. and concluded that the future requires not only an improved adoption of best applicable practices (BAP), but also a migration to best available technology (BAT). Examples of BAT are filtered, unsaturated, compacted tailings and reduction in the use of water covers in a closure setting. Examples of BAP bear on improvements in corporate design responsibilities, and adoption of Independent Tailings Review Boards. Specific recommendations are made in the body of the report.

1 | Introduction

Following the breach of the tailings storage facility at the Mount Polley Mine on August 4, 2014, the Government of British Columbia, through the Minister of Energy and Mines, together with the Williams Lake Indian Band and the Soda Creek Indian Band, established an independent expert engineering investigation and review panel (the Panel) to investigate and report on that breach.

1.1 PURPOSE OF THE PANEL

The purpose of the Panel is as follows:

- To investigate into and report on the cause of the failure of the tailings storage facility (TSF) that occurred on August 4, 2014 at the Mount Polley Mine (the Mine) in B.C.
- In addition, the Panel may make recommendations to government on actions that could be taken to ensure that a similar failure does not occur at other mine sites in B.C.
- The Panel is authorized, as part of its investigation and report, to comment on what actions could have been taken to prevent this failure and to identify practices or successes in other jurisdictions that could be considered for implementation in B.C.

Under its Terms of Reference, it is expected that the Panel will:

- Identify any mechanism(s) of failure of the TSF.
- Identify any technical, management or other practices that may have enabled or contributed to the mechanism(s) of failure. This may include an independent review of the design, construction, operation, maintenance, surveillance and regulation of the TSF.
- Identify any changes that could be considered to reduce the potential for future such occurrences.

1.2 PANEL MEMBERS

The members of the Panel are:

- Dr. Norbert R. Morgenstern (Chair), CM, AOE, FRSC, FCAE, Ph.D., P.Eng.
- Mr. Steven G. Vick, M.Sc., P.E.
- Dr. Dirk Van Zyl, Ph.D., P.E., P.Eng.

The detailed Terms of Reference are included as Appendix A.

2 | What Did the Panel Do?

2.1 PANEL ACTIVITIES

In furtherance of its mandate, the Panel undertook the following:

- It retained Thurber Engineering Ltd. (Thurber) to conduct field investigations, data compilation, laboratory testing, and analyses. All of this work proceeded under the direction of the Panel.
- It assembled and inspected related documents in the files of the Mine, its consultants who have acted as the Engineer of Record (EOR), and the Ministry of Energy and Mines (MEM).
- It solicited and collected relevant information from the public at large.
- It conducted a number of personal interviews to clarify information recorded in documents.
- It convened regular formal meetings with recorded minutes.
- It interpreted all of the above to arrive at conclusions and recommendations.

2.2 SUPPORTING INFORMATION

As directed by the Terms of Reference, the Panel has provided this final report, along with the appendices, to the Minister of Energy and Mines, the Williams Lake Indian Band and the Soda Creek Indian Band. The background reports and information used by the Panel for the preparation of this report were also made available to these parties through an online data room. The Panel considers the supporting information and substantiating documentation to be an integral part of its report that is necessary for a proper understanding of its findings.

The B.C. Ministry of Energy and Mines and Ministry of Environment, Conservation Officer Services, have directed the Panel to withhold some of the documents, and redact portions of other documents, so that the Panel's inquiry does not compromise any other investigations and to ensure it is in compliance with the privacy protection provisions of *Freedom of Information and Protection of Privacy Act* (FIPPA) (see Appendix A). The redaction of personal information was completed by Shared Services BC. As a result, these documents, which may have been cited in this report are not available at this time.

The background information was provided to the Panel by many different sources. Appendix B contains further details on background reports and information, and how these were organized and provided to the Minister of Energy and Mines, the Williams Lake Indian Band and the Soda Creek Indian Band.

Within the text of the report and appendices, specific documents are referenced by an endnote, which contains the document number as it relates to where it can be found in the data room. See Appendix B for more details.

Additional technical references are also cited by endnote directly within the body of this report. Endnotes can be found at end of each section of the report. The collected technical references can be found at the end of the report.

The observations of the Panel are supported by referenced documents where possible. The findings of the Panel are outlined in the sections of the report that follow. Conclusions and recommendations are presented in detail at the end of the report.

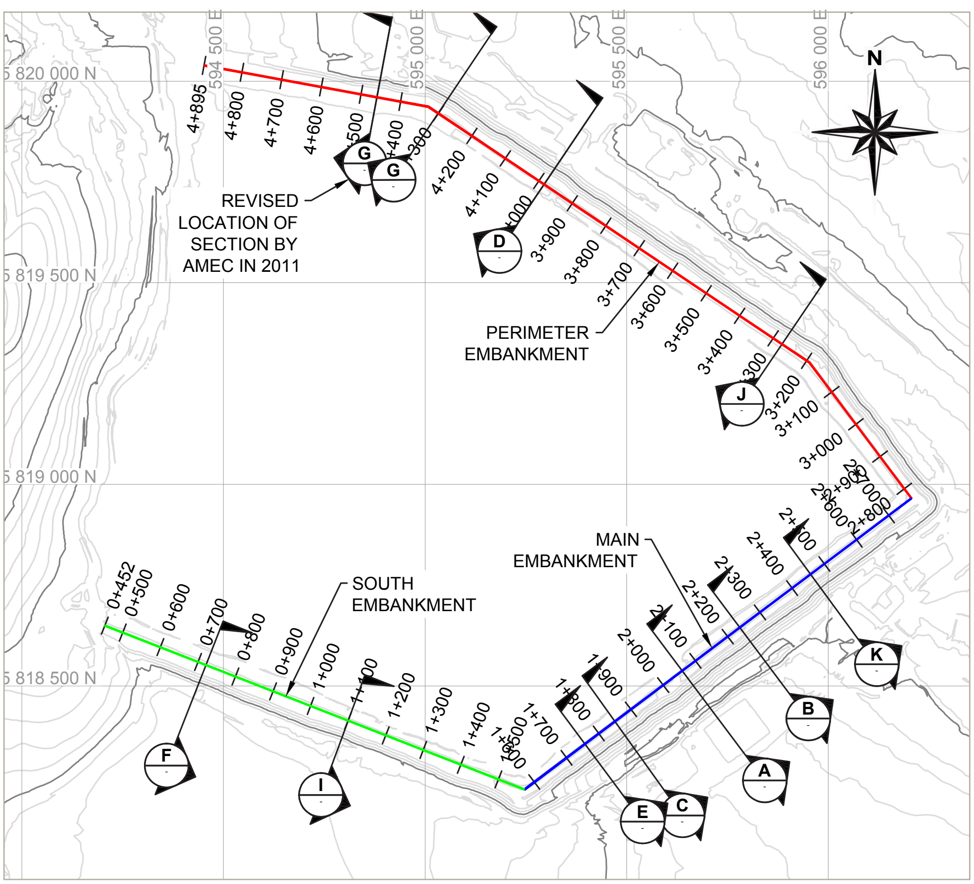
3 | Tailings Storage Facility (TSF)

3.1 DESCRIPTION OF TSF

Mount Polley Mining Corporation (MPMC) operates the Mine, and the British Columbia Ministry of Energy and Mines (MEM) is the Regulator. From the first approved and constructed portion of the TSF, in 1995, to early 2011, Knight Piésold (KP) was the Engineer of Record (EOR). Subsequently, AMEC assumed the responsibility as EOR and had that role at the time of the breach. BGC were to assume that responsibility after the 2014 construction season.

Figure 3.1.1 is a plan of the TSF adapted from the last As-Built Construction Report.[1] It indicates that the TSF was composed of three embankments: the Main Embankment, the Perimeter Embankment, and the South Embankment. The TSF is closed to the west by rising natural ground. The figure also indicates the location of instrumented control sections utilized by the succession of EORs. The breach occurred in the Perimeter Embankment near Section G.

FIGURE 3.1.1: TAILINGS STORAGE FACILITY PLAN



3 | Tailings Storage Facility (TSF)

3.2 CONSTRUCTION OF TSF AND POND ELEVATION

The Main Embankment and the Perimeter Embankment were the first to go into construction, with the Starter Dam completed in 1996. The South Embankment followed in later years. **Figures 3.2.1** and **3.2.2** present the sections of the Main and Perimeter Embankments at the end of the 2013 construction season. **Figure 3.2.1** is for the Main Embankment at Section A, approximately the highest section. **Figure 3.2.2** is for the Perimeter Embankment and represents the closest instrumented section (Section D) to the breach zone at the time of failure.

FIGURE 3.2.1: MAIN EMBANKMENT AT SECTION A

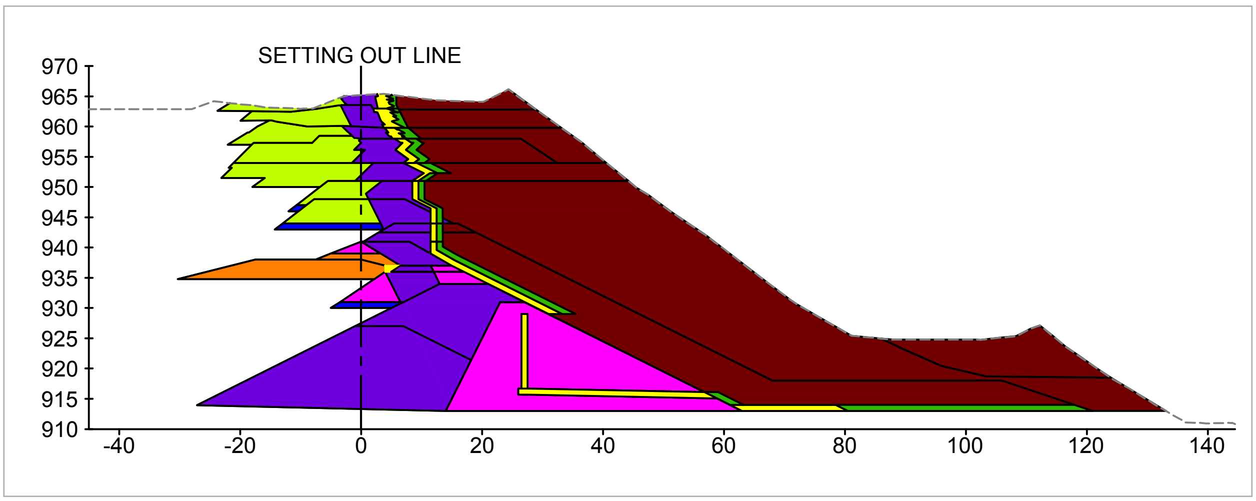
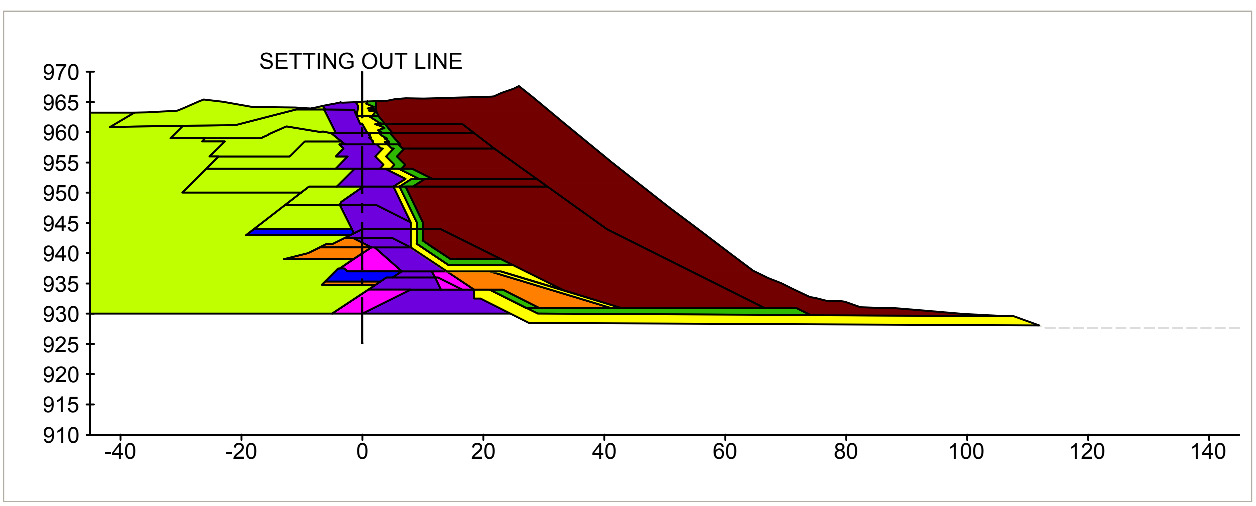


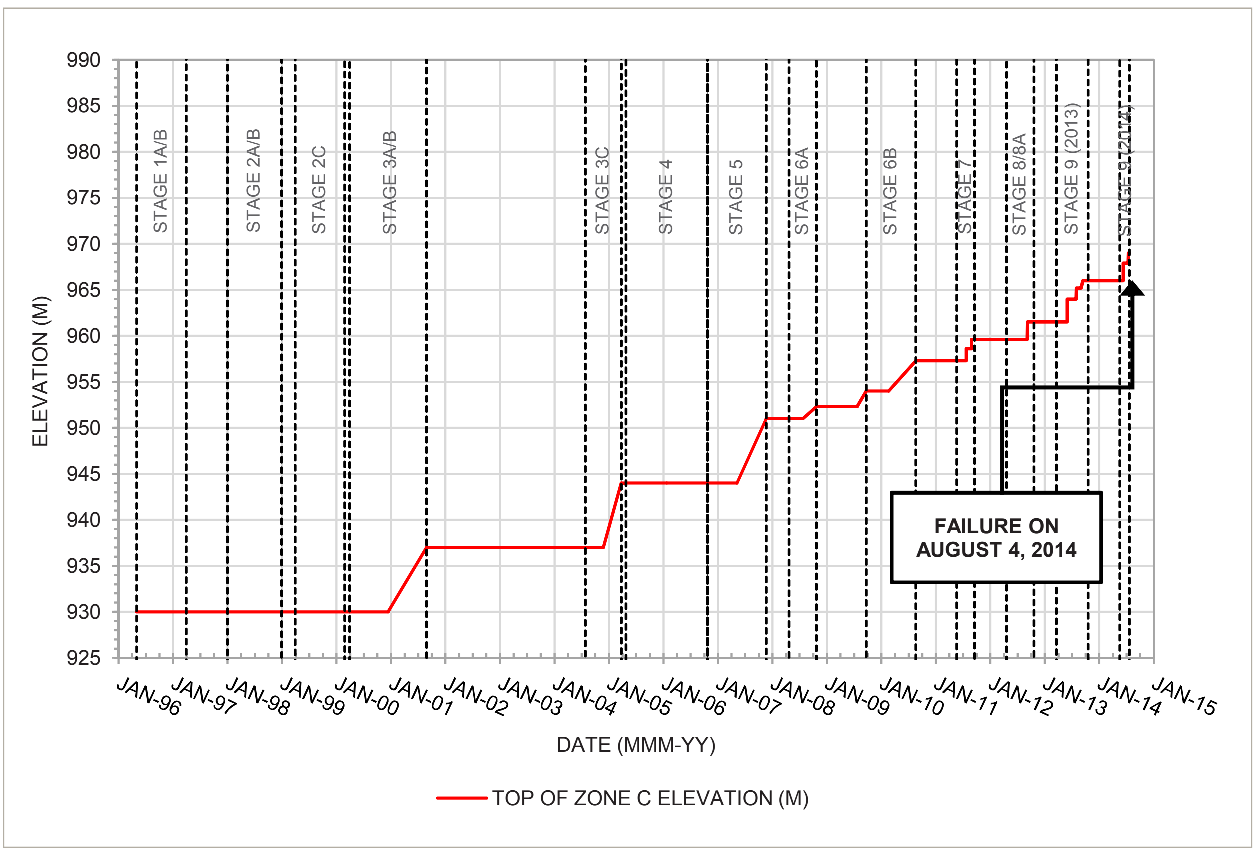
FIGURE 3.2.2: PERIMETER EMBANKMENT AT SECTION D



3 | Tailings Storage Facility (TSF)

The history of the construction of the embankments is summarized in **Figure 3.2.3,** which indicates each stage of dam raising up to the occurrence of the breach. The Starter Dam for the embankment was constructed in 1996 to a crest elevation of 927.0 metres (m). The embankments were subsequently raised together in stages as shown. Construction of the Stage 9 raise from approximately elevation (El.) 967.5 m to El. 970.0 m was started at the end of April 2014. Following completion of Stage 9, Stage 10 was planned to raise the crest to El. 972.5 m, which would have provided adequate storage to the end of September 2015. Stage 10 was under review for approval at the time of the breach.

FIGURE 3.2.3: MOUNT POLLEY TSF AND ZONE C (SHELL) TOP ELEVATIONS VERSUS TIME



3 | Tailings Storage Facility (TSF)

3.3 POND ELEVATION AT TIME OF BREACH

At the time of the breach, the TSF was permitted under MEM Permit M-200 with approval to raise the crest to El. 970 m. The breach occurred early on August 4, 2014 at a core elevation of El. 969.1 m. Loss of containment was sudden, with no identified precursors. The recorded pond elevation at 6:30 pm on August 3, 2014 was El. 966.83 m.

Loss of containment was sudden, with no identified precursors.

ENDNOTE

1) MP00044

4 | How Did This Dam Fail?

4.1 CLASSIFICATION OF DAM FAILURE

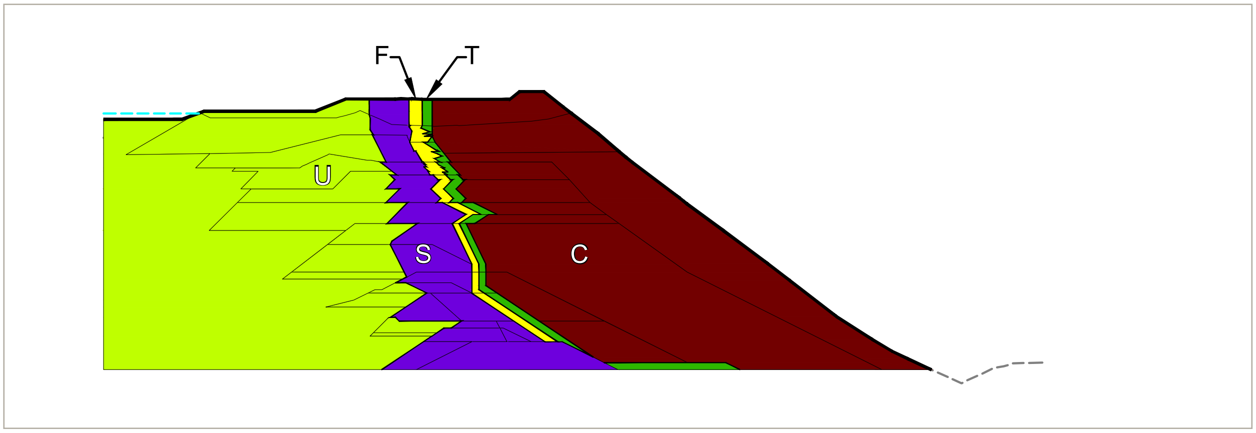
The following directional conventions are adopted throughout, with the dam as the frame of reference:

- Upstream — toward the impoundment interior
- Downstream — away from the impoundment interior
- Right — to the right, looking downstream
- Left — to the left, looking downstream

Figure 4.1.1 shows a simplified cross-section of the dam. It is constructed of both earth and rockfill and would be classified as a zoned earth and rockfill dam. The specific zones are:

U Zone	Upstream fill
C Zone	Rockfill
S Zone	Till core
F Zone	Filter
T Zone	Transition

FIGURE 4.1.1: SIMPLIFIED CROSS-SECTION OF THE MOUNT POLLEY DAM



4 | How Did This Dam Fail?

The impervious element of the dam is the till core (Zone S), composed of glacial deposits (till) excavated from selected borrow areas. The duty of the rockfill zone (Zone C) is to support the core, without which the core would not be stable. When seepage flows through the core or if it became cracked, its relatively fine-grained material might erode into the rockfill. The duty of the filter (Zone F) and transition (Zone T) is to collect any seepage coming through the core and to prevent fines from migrating out of it. Zone T is a transition to Zone C and it is intended to stop migration of filter material into Zone C. While Zone C is somewhat compacted to improve its density, this is not sufficient to preclude migration of Zone F into Zone C. Hence, a transition Zone T is needed.

Zone U is composed either of tailings or rockfill if tailings beach material cannot be delivered in time. It should be noted that the core of the dam is inclined slightly in an upstream direction. This configuration is known as modified centreline construction. Zone U provides support on the upstream side of the core. It also has other functions such as keeping clear water away from the core. Zone U tailings would tend to migrate into and fill any cracks that might develop in the core, preserving its function.

4.2 POTENTIAL FAILURE MODES

Assessing potential failure modes should be consistent with the characteristics of the breach; it was relatively sudden and with no apparent warning. In addition, by outward comparison, the Perimeter Embankment appears less vulnerable than the Main Embankment design section (**Figure 3.2.1**). The Main Embankment is higher, is designed on the same principles as the Perimeter Embankment, and Zone U has a less developed beach. Moreover, by the time of the breach, small movements had previously been detected in the Main Embankment foundation, and they were being managed by design and construction changes in response to observations. The Panel concluded that, in order to account for such an abrupt event in the Perimeter Embankment, local features likely prevailed.

The Panel concluded that, in order to account for such an abrupt event in the Perimeter Embankment, local features likely prevailed.

4 | How Did This Dam Fail?

4.3 FOUR CLASSES OF FAILURE MECHANISMS CONSIDERED

Based on the experience of the Panel with both water and tailings dams, the Panel determined that the following four classes of failure mechanisms required consideration:

- Human intervention
- Overtopping
- Piping and cracking
- Foundation failure

Before considering each in turn, it is necessary to understand the timeline of activities at the site prior to the failure.

The timeline constructed from construction and personal reports is presented in **Table 4.3.1**. The breach section extends approximately from survey station (Sta.) 4+200 to 4+300. (refer to **Figure 3.1.1**). Key observations are:

- Last construction ending at 6:30 pm, August 3, 2014
- Site observation indicating no issues at 10:30 pm, August 3, 2014
- Operations at perimeter seepage pond, no issues at 11:45 pm, August 3, 2014
- Perimeter seepage pond water fluctuation beginning at 12:45 am, August 4, 2014
- Power lost (likely due to breach) at 1:15 am, August 4, 2014
- Breach identified at 2:05 am, August 4, 2014

TABLE 4.3.1: TIMELINE OF EVENTS AND ACTIVITIES AT BREACH SECTION AND ADJACENT AREAS

DATE	ACTIVITY	POND El.	SOURCE
7/10	Zone F (filter) trenching from 4+300 to 4+750, El. 967.0	966.55	Construction Daily Report (MPMC)
7/14	Zone S (till) placement from 4+305 to 4+925, El. 968.5	966.55	Construction Daily Report [1]
7/15	Zone S (till) placement from 3+980 to 4+305, El. 968.5 Zone S (till) placement from 4+420 to 4+770, El. 968.8	966.55	Construction Daily Report [1] *
7/16	Zone S (till) placement from 3+990 to 4+768 @ El. 968.5 (completed to PE pipe) [i] Zone S (till) placement from 4+395 to 4+757 @ El. 968.8	966.53	Construction Daily Report [1] *
7/17	Zone S (till) placement from 3+995 to 4+395 @ El. 969.1 (completed to PE pipe)	966.60	Construction Daily Report [1] *
7/24	Zone C (rock) placement from 4+525 to 4+650, El. 968.8	966.68	Construction Daily Report [1] *
	Extreme rainfall, Perimeter overflowing [ii]		TSF Leadhand Report
7/25	Zone C (rock) placement from 4+335 to 4+525, El. 968.8	966.73	Construction Daily Report [1]*
	Perimeter still in "Red" with all pumps running, only 1.7 metres left in perimeter overflow		TSF Leadhand Report [2]

4 | How Did This Dam Fail?

TABLE 4.3.1: TIMELINE OF EVENTS AND ACTIVITIES AT BREACH SECTION AND ADJACENT AREAS *continued*

DATE		ACTIVITY	POND El.	SOURCE
7/26		Perimeter held @ "6" on scale all day but still overflowing Till pit level went up 20 cm overnight Retrieved piezo below corner 1		TSF Leadhand Report [2]
7/28		Zone C (rock) placement from 4+180 to 4+335, El. 968.8	966.70	Construction Daily Report [1]*
8/01		Zone C (rock) placement (grading down near Corner 1), El. 969.0 Raising of PE pipe in the C zone	966.80	Construction Daily Report [1]*
		Last placement of Zone C (rock) in breach area with four 733s (60T) and one D-8R		Panel Interview 10/22/14
8/02		Placing Zone C on the PE pipe after raising it	966.82	Construction Daily Report [1]*
8/03	6:30 am to 6:30 pm	Placing C zone on the PE pipe after raising it (completed) Grading C Zone (rock) from corner 5 to the PE pipe that has been recently placed by Peterson	966.83	Construction Daily Report [1]*
	10:30 pm	Good berm, good slope, no visible cracks		Shifter Dump Logbook (Mine Ops), B-crew night shift [3]
	11:00 pm	East Perimeter Pond going to alarm in high level within the hour		Dam Breach Report [4]
	11:30 pm	Second pump (perimeter pond) started, nothing unusual noticed		Dam Breach Report [4]
	11:45 pm	Drove from perimeter pond across dam crest to PE pipe and back to Corner 5 (across breach area), nothing unusual noticed		Panel Interview 10/22/14
	12:00 midnight	Second pump drawing down perimeter pond water level (recollection of control instrumentation)		Panel Interview 10/22/14
8/04	12:15 am	Pond water starts to level out (recollection of control instrumentation)		Panel Interview 10/22/14
	12:45 am	Pond water level starts to slightly increase (recollection of control instrumentation)		Panel Interview 10/22/14
	1:00 am	Pond water level rising sharply (recollection of control instrumentation)		Panel Interview 10/22/14
	1:15 am	Lights went out in electrical shop, mill shut down, pond water level spikes sharply (recollection of control instrumentation)		Dam Breach Report [4] Panel Interview 10/22/14
	2:05 am	Dewatering operator discovers that tailings dam had breached		Dam Breach Report [4]

* PHOTO AVAILABLE IN CONSTRUCTION DAILY REPORT.

[i] "PE PIPE" IS THE RETURN-WATER HDPE LINE FROM THE SEEPAGE RECYCLE PUMP THAT CROSSES THE DAM CREST AT THE LOCATION OF SECTION D, APPROX STA. 3+960 (SEE PHOTO IN CONSTRUCTION DAILY REPORT OF 8/02/14).

[ii] "PERIMETER" REFERS TO PERIMETER SEEPAGE POND. "OVERFLOW" REFERS TO OVERFLOW FROM PERIMETER SEEPAGE POND INTO TILL BORROW PIT (PANEL INTERVIEW, 10/22/14).

4 | How Did This Dam Fail?

4.3.1 HUMAN INTERVENTION

Human intervention may be accidental, such as discharge from a tailings line eroding the structure in an uncontrolled manner, or wilful destruction. A tailings pipeline on the Perimeter Embankment crest was not in service at the time of the breach, and the Panel has found no other evidence of failure due to human intervention.

4.3.2 OVERTOPPING

Although water management had been challenging in later years, and an episode of overtopping over portions of the Perimeter Embankment had occurred in May 2014, freeboard was being carefully monitored around the time of the breach as a result of prior insistence on the part of the Ministry of Energy and Mines (MEM). The freeboard with respect to the core at the time of the failure was 2.3 metres (m).[5]

The Panel has found no evidence of failure due to overtopping prior to breach development.

The Panel has found no evidence of failure due to overtopping prior to breach development.

4.3.3 PIPING AND CRACKING

Piping and cracking of the core of an earth-rockfill dam can lead to internal erosion and ultimately loss of containment. This is one of the most common causes of failure of earth dams and has been much studied. The failure of the Omai Tailings Dam[6] provides an example of a failure by piping and internal erosion.

The following factors were of concern to the Panel:

1) Modified centreline tailings dams, while within precedent, are disposed to longitudinal cracking.
2) Following Stage 5, the core width was reduced to 5 m, which is thin for the planned hydraulic head; again, this has precedent but requires careful filter and transition design and construction.
3) The filter and transition were particularly thin and required meticulous care to be constructed as intended.
4) Details of filter and transition construction in as-built drawings indicated departure from intended design.[7]
5) Much of the as-placed filter material failed to meet applicable filter criteria and requirements for internal stability of its grading.
6) The core had been overtopped in one location for a brief period in 2014, resulting in softening and enhanced deformability.
7) The core was not contained by the steep rockfill shell in as stiff a manner as might have been possible.
8) A cavity was detected in the core remnant of the left abutment of the breach that was the result of internal erosion, see Appendix C.
9) Observed flow to the seepage collection system exhibited a transient spike on April 22, 2013, of the kind

sometimes characteristic of internal erosion (see Appendix F for details).

Notwithstanding these concerns, the Panel notes:

1) No abnormal seepage observations were detected except for the spike on April 22, 2013 (see Appendix F).
2) Sonic drillholes were located as close to the abutments of the breach as safely possible. They did not detect any suspicious piping pathways.
3) Excavation of the right abutment of the breach did not find any piping pathways through the core.
4) Grading of samples of filter material recovered from the breach area indicate that internal erosion did not produce large flows or overall loss of core integrity (see Appendix C).

Accordingly, and despite the concerns identified by the Panel, it did not find evidence that the breach was caused by piping and/or cracking resulting in uncontrolled internal erosion.

4.3.4 FOUNDATION FAILURES

Observations from the Surface Investigations (see section 5.1 and Appendix C for details) provided clear evidence for shearing, bodily lateral displacement, and rotation of the embankment that resulted in the breach. The Panel concluded that the primary cause of the breach was dislocation of the embankment due to foundation failure. This resulted in loss of containment of both the clear water contained in the tailings storage facility (TSF), and tailings, which flowed out of the breach. Clearly, the foundation has behaved in a weaker manner than anticipated in the design. A major focus of this investigation was therefore to determine the foundation characteristics that account for the observed failure mode and to compare the outcome with the design basis.

Observations from the Surface Investigations provided clear evidence for shearing, bodily lateral displacement, and rotation of the embankment that resulted in the breach.

A number of circumstances can contribute to such weak behaviour, and all require careful assessment.

It is well-known that glaciated terrain can be exposed to glacial drag forces and leave in the underlying sediments and bedrock, if relatively soft, continuous weak surfaces at the residual strength of the material. The residual strength is the weakest resistance that the material can offer and arises from preferred orientation of platy clay particles. Valley rebound folding and expansion in soft bedrock can also result in weak residual strength materials, but these processes have not acted at the TSF. Examples of large tailings facilities on glacially sheared material at

4 | How Did This Dam Fail?

low strengths are the Mildred Lake Settling Basin at the Syncrude Canada Ltd. site [8] and the large TSF at the Zelazny Most Copper Mine. [9] In both cases, movements are slow and are managed by adaptive response to observations.

Another source of unanticipated behaviour can be a deposit within the foundation of a dam that exhibits pronounced strain-weakening behaviour; that is, it loses considerable resistance once its peak resistance is attained. This type of behaviour was discovered during the forensic investigation into the Aznalcollar (Los Frailes) Tailings Dam failure in Spain. [10] The movements in that case were sudden, without any observable precursors. The instrumentation at the time was minimal.

A further source of unanticipated behaviour arises when a structure is being built in stages on a soft substrate that is contractant; that is, it tends to contract, or densify. When such a soil is subjected to shearing due to loading that occurs slowly, the resulting volume changes strengthen the soil as it densifies. This is known as drained loading. However, if the contractant soil were to be loaded too quickly for water to be expelled and permit volume change, pore pressures develop that weaken the soil. This is known as undrained loading, and the resistance is less than its drained equivalent.

Undrained response can also be initiated if the soil displays a rapid reduction in resistance as yielding is initiated, even under drained conditions. This has sometimes been called spontaneous liquefaction when flowslides develop. While the Mount Polley failure was not sufficiently mobile to be regarded as a flow, the concept of spontaneous undrained response cannot be disregarded in a broadly based inquiry such as this. The implications for stability of the undrained response of soft, contractant soils to staged construction were presented at length in a classic paper by Ladd [11] and are discussed in a widely accepted graduate-level text by Duncan and Wright. [12] The Kingston fly ash slurry spill is an example of a TSF that failed by this undrained mechanism (http://www.tva.gov/kingston/rca/).

All of the above hypotheses regarding the characteristics of the ground conditions in the breach zone were considered in the Technical Commentary that follows. The Technical Commentary presents the findings arising from both surface and subsurface investigations, laboratory studies, computational analyses, and design, construction, and monitoring reviews, in support of the explanation of the cause of failure.

4 | How Did This Dam Fail?

ENDNOTES

1) MP10000

2) MP10021

3) MP10022

4) MP10013

5) MP00188

6) Vick, S.G., 1996. The failure of the Omai Tailings Dam. *Geotechnical News*, September, pp. 34-39.

7) MP00044

8) Alencar, J., Morgenstern, N.R. and Chan, D.H., 1994. Analysis of foundation deformations beneath the Syncrude tailings dyke. *Canadian Geotechnical Journal*, Vol. 31, pp. 868-884.

9) Jamiolkowski, M., 2014. Soil mechanisms and the Observational Method: Challenges at the Zelazny Most copper tailings disposal facility. *Geotechnique*, Vol. 64, pp. 590-618.

10) Gens, A. and Alonso, E.E., 2006. Aznalcollar dam failure – Part 2: Stability conditions and failure mechanism. *Geotechnique*, Vol. 56, pp. 185-201.

11) Ladd, C.C., 1991. Stability evaluations during staged construction. *Journal of Geotechnical Engineering*, American Society of Civil Engineers, Vol. 117, pp. 540-615.

12) Duncan, J.M. and Wright, S.G., 2005. *Soil Strength and Slope Stability*. John Wiley and Sons, Inc., New Jersey, 298 p.

5 | Panel Observations

5.1 SURFACE INVESTIGATIONS

Surface investigations of the breach and adjacent areas were conducted to gather evidence about the cause of the failure, to document this evidence, and to provide necessary context for related Panel activities. Appendix C provides a comprehensive account of the surface investigations from which this summary has been compiled. The electronic version of Appendix C also contains a virtual three-dimension (3-D) flyover to help orient the reader to features and interrelationships described here.

5.1.1 DATA COLLECTION

The surface investigations made use of imagery from a variety of sources, field mapping on the ground, and exploratory excavation of key features. Data sources and collection activities included the following:

- Review of pre-failure satellite imagery
- Review of a helicopter video made by the Cariboo Regional District during failure
- Review of post-failure helicopter photos by the Panel and airphoto stereopairs
- Review and preprocessing of Panel ground photos
- Preparation of topographical base maps and cross-sections
- Field mapping of ground features and exposures
- Excavation and logging of exploratory works in a remnant section of the dam core

5.1.2 KEY FEATURES

An oblique view of the breach area looking upstream is provided in **Figure 5.1.1**. This and the following image were obtained from the Cariboo Regional District's video. The video was taken on the morning of August 4, 2014, about 8 hours after breach initiation with breach outflow still in progress. It provides a unique opportunity to observe how many of the key post-breach features were formed.

5 | Panel Observations

FIGURE 5.1.1: VIEW LOOKING UPSTREAM THROUGH THE BREACH (ARROW SHOWS DIRECTION OF OUTFLOW)

The labelled features in **Figure 5.1.1** can be interpreted with reference to the internal zoning of the dam previously provided as **Figure 4.1.1**. On the upstream side of the breach, remnant projections of the dam core (S) can be seen on the left and right abutments. The projection on the right abutment acts like a jetty in directing flow toward the left abutment.

Zone C rockfill (C) is exposed on the left abutment, where it has been eroded by these redirected breach outflows. On the right abutment, the surface of the displaced rockfill (D) was subject to erosional overflow during earlier stages of breach development. It was subsequently protected from erosional undercutting in the main channel by the projecting core remnant and eddies that developed downstream.

The whaleback feature (W) is a linear, uplifted ridge of foundation till that extends across the entire width of the breach. Highly erosion-resistant in both native and compacted forms, the upthrusted till here acts as the control section for breach outflow.

5 | Panel Observations

A reverse-angle perspective looking downstream through the breach is provided in **Figure 5.1.2**. It shows the damage to the upstream side of the dam and the processes that caused it.

FIGURE 5.1.2: VIEW LOOKING DOWNSTREAM SHOWING UPSTREAM SIDE OF DAM AND REMAINING TAILINGS

At this point, two major flow channels have developed within the impoundment that converge at the upstream entry to the breach. In the distance (centre left), one of these can be seen flowing along the left side of the dam. As is did so, it eroded away the supporting tailings. This caused the upstream side of the dam to collapse, leaving the prominent near-vertical face. These structural effects are again best appreciated with reference to **Figure 4.1.1**.

Conditions adjacent to the right side of the dam illustrate how the combined action of fluvial erosion and tailings flowsliding produced similar effects. The active flowslide (B) has left a semicircular headscarp that is progressing back and undermining the Zone U tailings supporting the upstream side of the dam core. Arcuate headscarps of earlier flowslides (A) have captured and concentrated overland flows from surface water remaining in the impoundment. The resulting cascades readily transport flowslide debris, while at the same time causing backward erosion of the headscarps by scour within their terraced plunge pools.

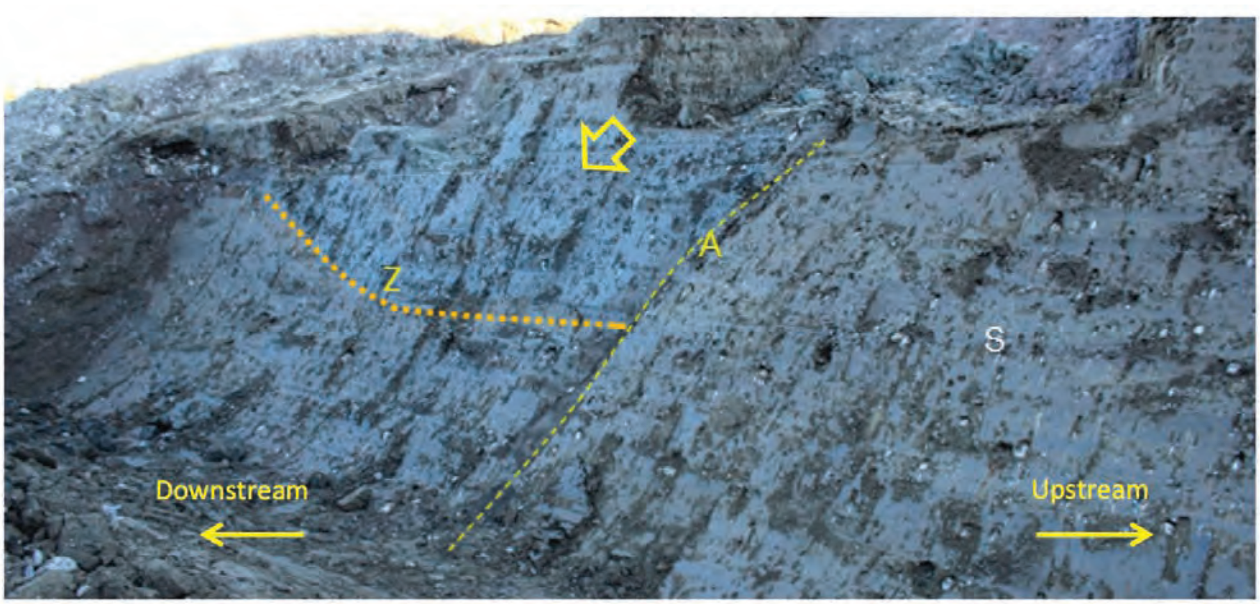
5 | Panel Observations

5.1.3 FOUNDATION SLIDING

The surface investigations produced direct evidence for foundation sliding as the initiating mechanism for the breach. This is most clearly demonstrated by a shear surface observed within the remnant core projection on the right abutment at the location shown previously in **Figure 5.1.1**.

Figure 5.1.3 shows an excavated exposure of the shear surface (A) through the Zone S core material (S). The marker bed (Z) was not present on the upstream footwall side (right in photo), indicating at least 3.3 metres (m) of downthrow on the downstream hanging wall. Appendix C, section 3.7, contains more detail on the orientation and configuration of the shear surface.

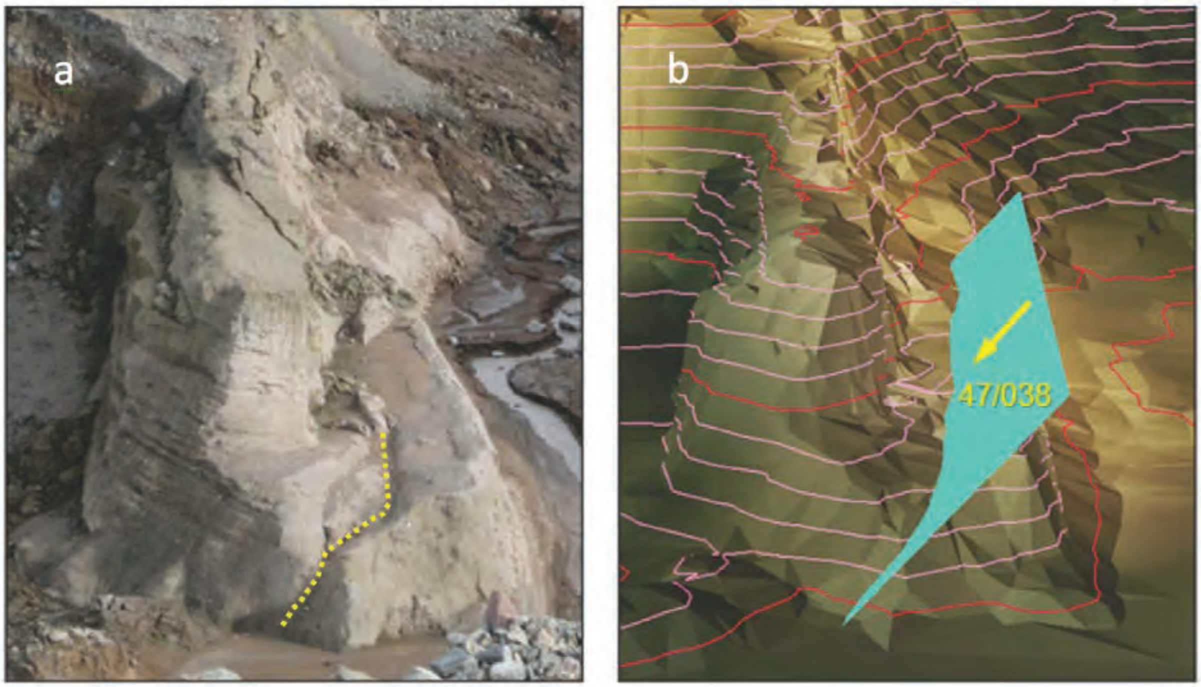
FIGURE 5.1.3: SHEAR SURFACE THROUGH REMNANT DAM CORE (ARROW INDICATES DIRECTION OF DOWNDROP)



The surface trace and 3-D orientation of the shear are shown on the core remnant in Figure 5.1.4, with a dip angle and direction as indicated.

5 | Panel Observations

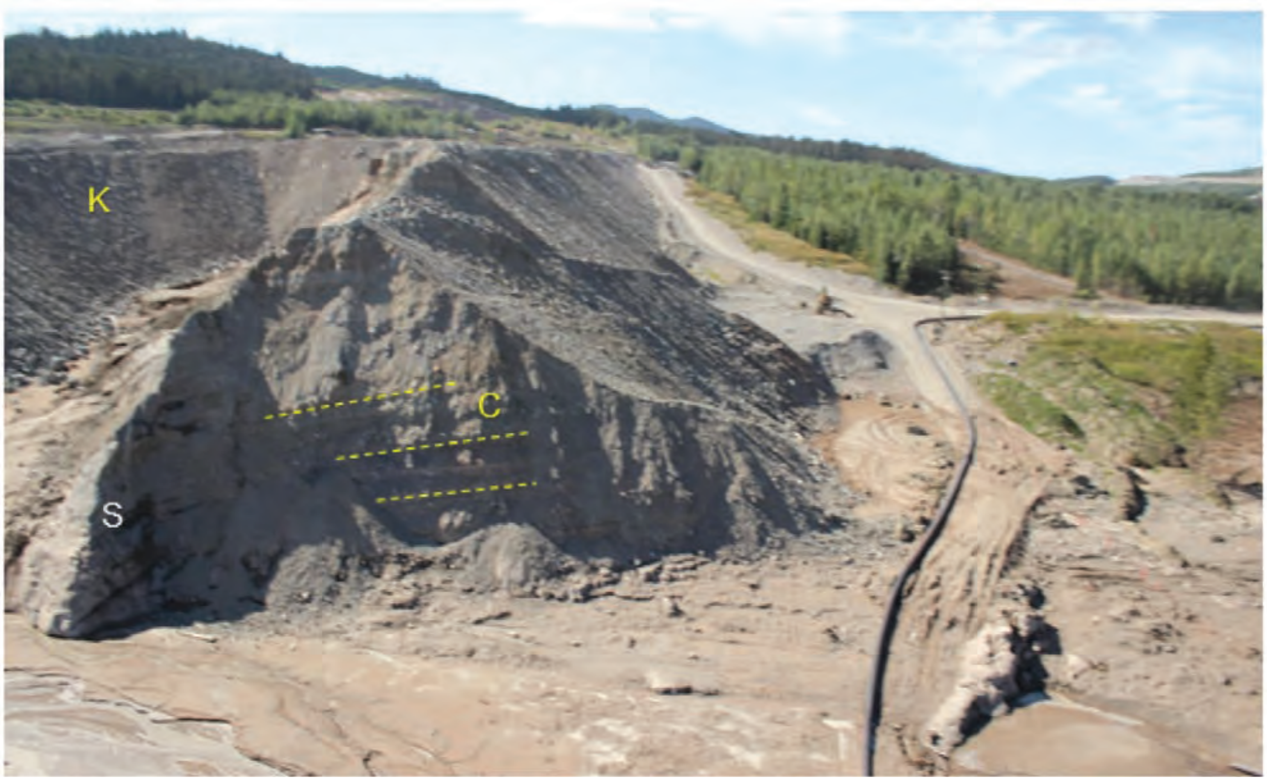
FIGURE 5.1.4: PHOTO (a) AND SURFACE MODEL (b) SHOWING SHEAR SURFACE ORIENTATION



5 | Panel Observations

Other artifacts of foundation sliding are evident elsewhere. As indicated in **Figure 5.1.5**, lift lines in the Zone C rockfill on the left abutment (C) are tilted at an inclination of 7° to 10°, with corollary inclinations on the right abutment of 5° to 14°. Also shown in **Figure 5.1.5** are the Zone S core (S), with a containment dike (K) under construction in the background. Scarps higher on the left abutment were produced by post-sliding downdrop of large slump blocks into the breach due to erosional undercutting at foundation level.

FIGURE 5.1.5: APPARENT BEDDING ROTATION ON LEFT ABUTMENT OF BREACH (SEPT. 4, 2014 PHOTO)



5 | Panel Observations

Figure 5.1.6 shows the right abutment, with the left abutment in the background. Noteworthy features include open cracks (O) and headscarps (H) at higher elevations. At the downstream toe, upthrust of foundation till (L) ranging from 2.8 m to 3.5 m has occurred along an alignment collinear with the whaleback (W).

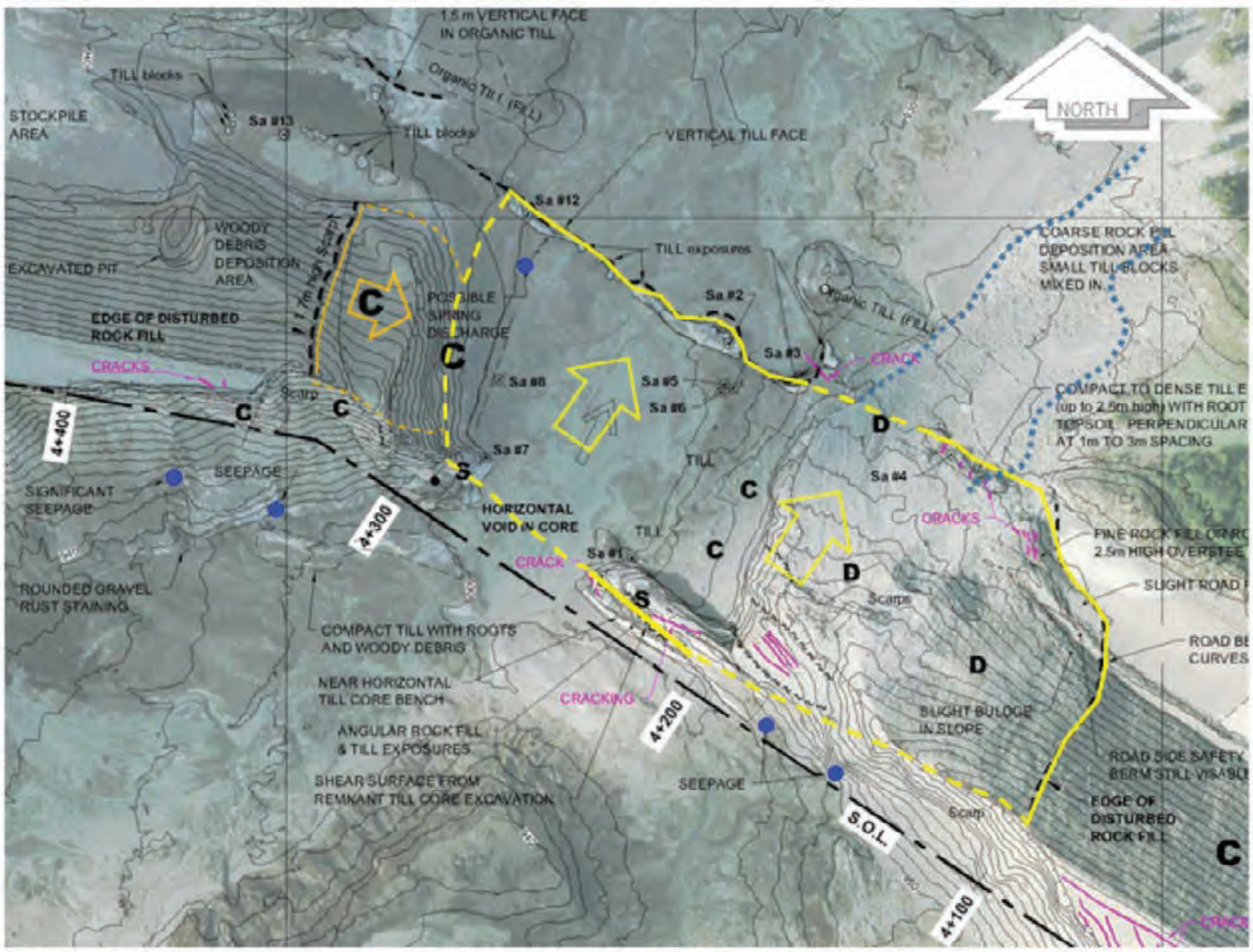
The mass of rockfill (D) from the upper headscarps to the lower upthrusted till was rotated and displaced by foundation sliding. It was preserved when surface sheet flow was terminated by breach downcutting on the left side. From displacement of surface lineations, lateral (downstream) translation of 11 m occurred in the vicinity of the arrows in the figure.

FIGURE 5.1.6: SLIDING-RELATED FEATURES AT RIGHT ABUTMENT (SEPT. 4, 2014 PHOTO)

5 | Panel Observations

Surface investigations delineate the limits of foundation sliding given in **Figure 5.1.7**, with the solid and dashed yellow lines indicating observed and inferred boundaries, respectively. These are superimposed on the post-failure orthophoto and contours to show the extent of mass movement in relation to the breach. Arrows indicate directions of movement from surface observations.

FIGURE 5.1.7: PLAN SHOWING DIRECTION AND EXTENT OF MASS MOVEMENTS



5 | Panel Observations

Movements are summarized in **Table 5.1.1** below.

TABLE 5.1.1: MEASURED AND INFERRED SLIDE MOVEMENTS

LOCATION	DISPLACEMENTS AND ORIENTATIONS	
DOWNSTREAM TOE	Vertical: Horizontal:	2.8 to 3.5 m upward 11 m downstream
UPSTREAM SHEAR SURFACE	Vertical: Dip:	>3.3 m downward 47 degrees
RIGHT ABUTMENT	Rotation:	5 to 14 degrees
LEFT ABUTMENT	Rotation:	7 to 10 degrees

5 | Panel Observations

5.1.4 INTERNAL EROSION

A void shown in **Figure 5.1.8** was observed on the upstream side of the left abutment, measuring 0.7 m by 0.3 m and extending back 1.1 m into the Zone S core. The angular corners and abrupt transitions at the opening are distinct from the smoother, more rounded surfaces produced by surface erosion at other locations.

FIGURE 5.1.8: VOID ON UPSTREAM SIDE OF LEFT ABUTMENT

5 | Panel Observations

Additionally, Zone F filter material immediately downstream from the core was sampled in the right abutment excavation. Gradation data show that none of these samples met filter criteria that would have enabled them to prevent transport of fines from the till. Together, these factors suggest internal erosion as the likely cause of the left abutment void.

This filter material also has an internally unstable gradation, such that its finer fraction is free to pass through the voids in the coarser fraction under sufficient flow velocity. However, the fact that this finer fraction is still present means that high discharge through the filter, and therefore through the core, did not occur. Moreover, painstaking excavation and thorough logging found no evidence of other such voids in the excavated core. Nor were continuous cracks or softened zones indicative of hydraulic fracturing discovered. These factors suggest that internal erosion was not pervasive over the breach area or sufficiently severe to have compromised core integrity overall.

These factors suggest that internal erosion was not pervasive over the breach area or sufficiently severe to have compromised core integrity overall.

5 | Panel Observations

5.2 SUBSURFACE INVESTIGATIONS

5.2.1 INTRODUCTION

Following the breach of the Mount Polley Perimeter Embankment, site investigation programs were initiated by the Mines Inspector team with Klohn Crippen Berger (KCB) as the geotechnical lead, Mount Polley Mining Corporation (MPMC) with Golder Associates (Golder) as the geotechnical lead, and the Panel, with the support of Thurber Engineering Limited (Thurber). This section summarizes the Panel's program, its outcome, and key findings that affect other aspects of the Panel's activities. Appendix D provides further details of Thurber's work, results and interpretations. Results of the KCB work are available in Appendix B. [1] The Panel relied on factual data collected by both Thurber and KCB, but made its own interpretations of these data.

5.2.2 JOINT SITE INVESTIGATION

In early September 2014, MPMC invited the Panel to participate in a coordination meeting with KCB and Golder to review proposed joint site investigation plans consisting of:

- Geophysics — Direct current resistivity, induced polarity and seismic refraction surveys.
- Drilling and coring — Sonic drilling to allow initial foundation characterization at the dam breach and adjacent areas, and mud rotary drilling and sampling with focus on clays and silts designated the Upper Glaciolacustrine Unit (Upper GLU).
- In situ testing and instrumentation — cone penetration test (CPT) and piezometer and inclinometer installation at selected locations.

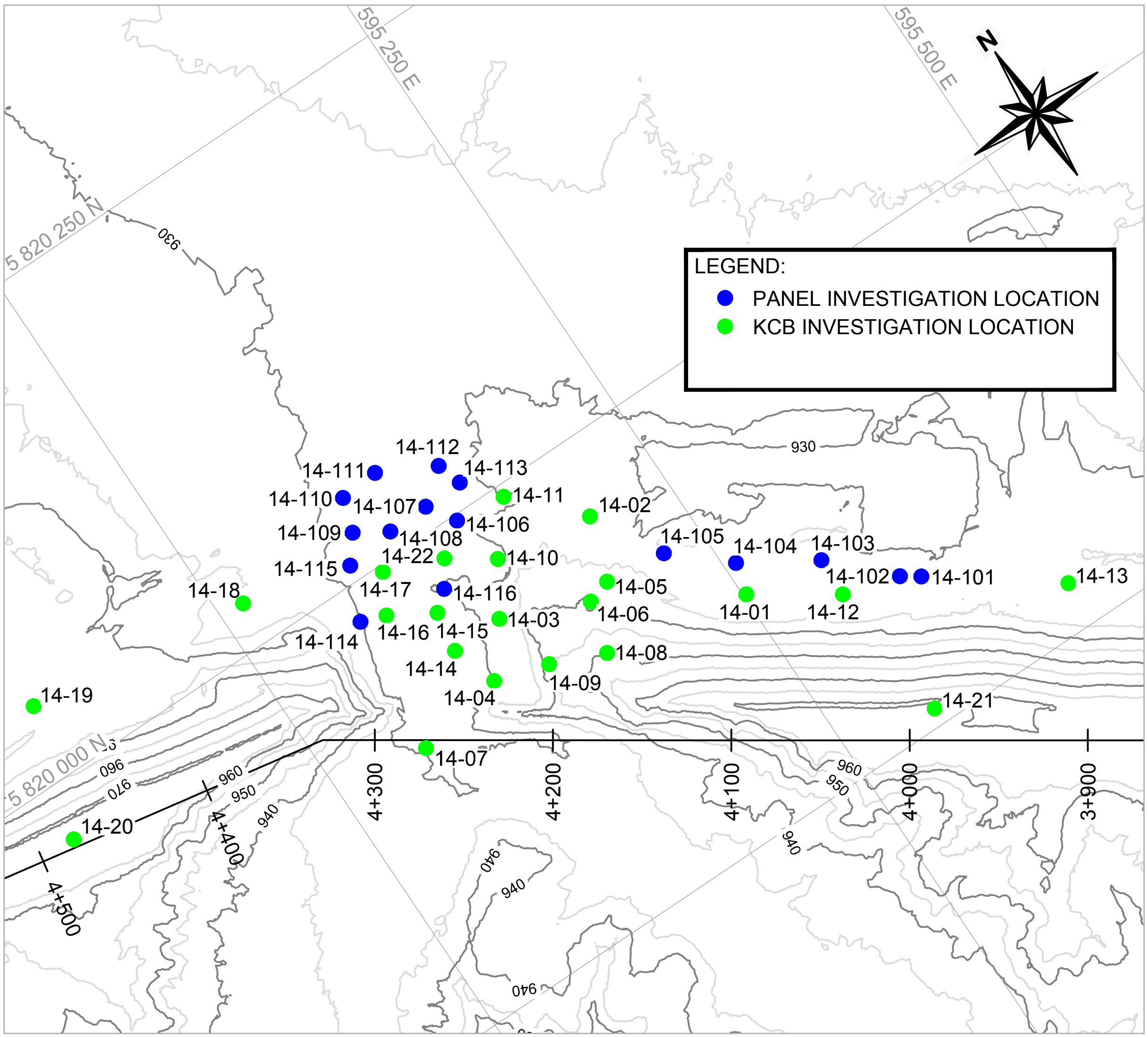
Safe work plans had to be implemented to establish access limits with respect to the remaining breach abutments. These limits influenced the locations of the final geophysics lines and the drillhole locations.

KCB field engineers took large numbers of samples from the sonic cores for routine or index testing in the KCB laboratory. Index test results were shared with the Panel. Thurber also collected samples for index testing from a number of locations during the site mapping and other activities for testing in the Thurber laboratories. All index test results are presented in Appendix D, Attachment 7.

Daily reports describing fieldwork progress were shared with all parties. Weekly conference calls, in which the Panel participated, served to further coordinate the fieldwork and provide updates. Adjustments were made to the detailed locations of the geophysics lines as well as drillholes as the program was implemented. **Figure 5.2.1** shows the final locations of the joint site investigation holes in and around the breach area.

5 | Panel Observations

FIGURE 5.2.1: JOINT AND PANEL SITE INVESTIGATION DRILLHOLE LOCATIONS



Thurber's field engineer observed the sonic drilling by KCB and logged all the sonic holes in parallel with the KCB personnel. The Thurber logs of the KCB sonic holes are provided in Appendix D, Attachment 1. Related seismic and resistivity surveys are also described in Appendix D, Attachment 1.

5.2.3 PANEL SITE INVESTIGATION

About half of the locations for the KCB investigation were located in the failed section footprint as well as through the remaining embankment into the underlying foundation. The Panel developed a separate field program that allowed in situ testing and sampling at a larger number of locations where foundation materials had not been preloaded by the embankment. The Panel site investigation consisted of:

- CPT and vane testing to characterize the foundation stratigraphy and to identify sampling locations for advanced shear and consolidation testing (refer to section 5.3 for further details of the laboratory testing).
- Mud rotary drilling to obtain disturbed and undisturbed samples of the Upper GLU and other units for laboratory testing.
- Pressuremeter testing in the till to obtain shear strength and shear modulus values.
- Drilling and sampling using Large Penetration Testing (LPT) in selected areas of foundation till.

Details of drilling methods, in situ testing and related information are included in Appendix D. Excavation, sampling and related laboratory testing are described in Appendix C.

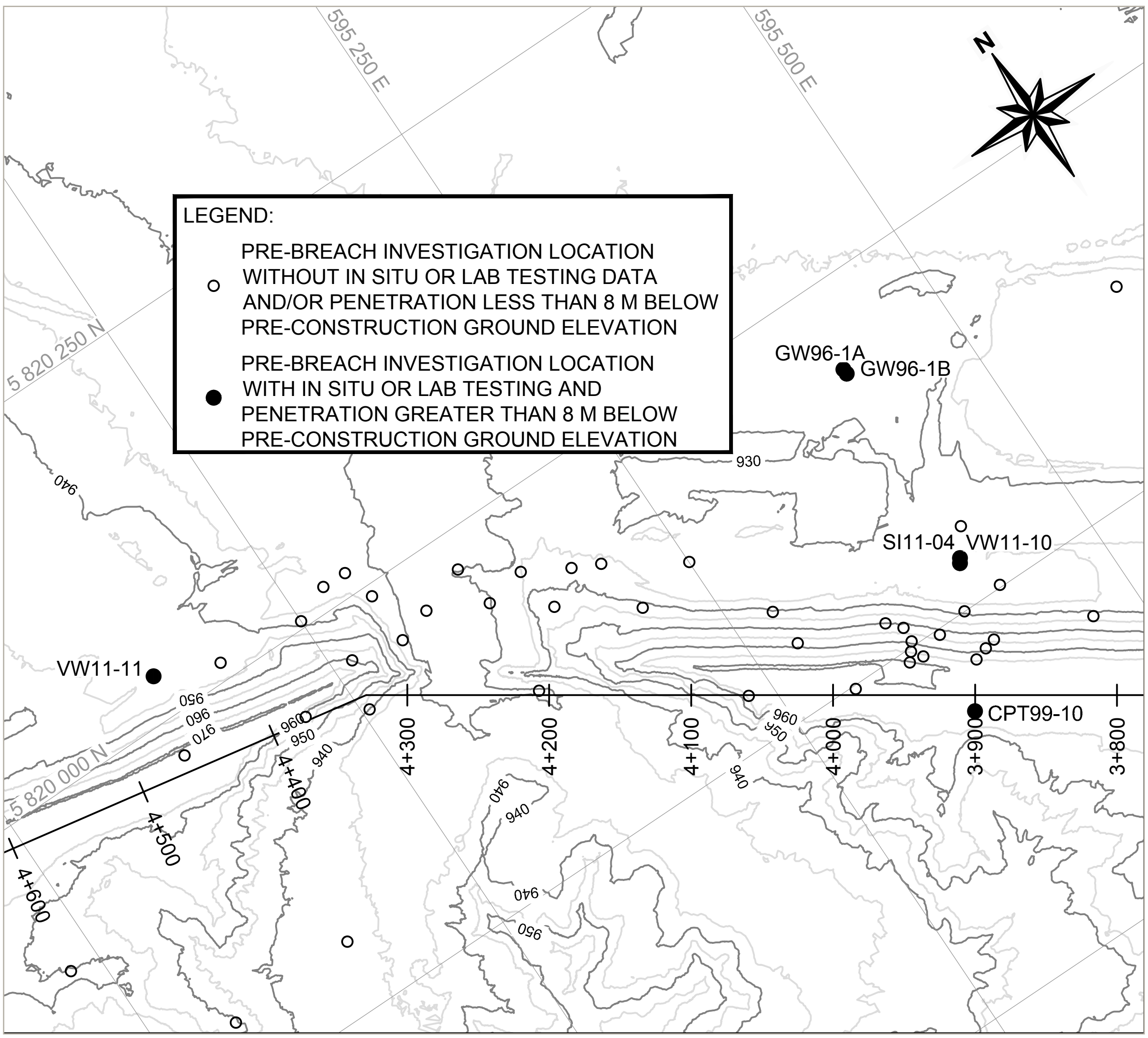
5.2.4 PRE-FAILURE SITE INVESTIGATIONS IN BREACH AREA

Appendix D provides a summary of pre-failure site investigations for the Mount Polley tailings storage facility (TSF). Knight Piésold (KP) performed site investigations in the early to mid-1990s for the design of the facility. Additional site investigations and laboratory testing were done during operations, notably a sonic drilling and instrumentation program implemented by AMEC in 2011. **Figure 5.2.2** shows all the geotechnical drillhole locations for pre-failure investigations in the breach area.

While a large number of locations are shown, many were condemnation holes or shallow test pits of limited usefulness for embankment design purposes. As subsequently discussed, the Panel found the critical soils in the breach area at depths of about 8 m. There are only four locations where the holes were deeper than 8 m and where in situ or laboratory testing was done. None of these locations were in the area where the breach occurred.

5 | Panel Observations

FIGURE 5.2.2 PRE-FAILURE SITE INVESTIGATION DRILLHOLE LOCATIONS IN BREACH AREA



Based on the subsurface investigations and related laboratory data, the Panel derived several key findings that informed its larger efforts. These are discussed in the following sections.

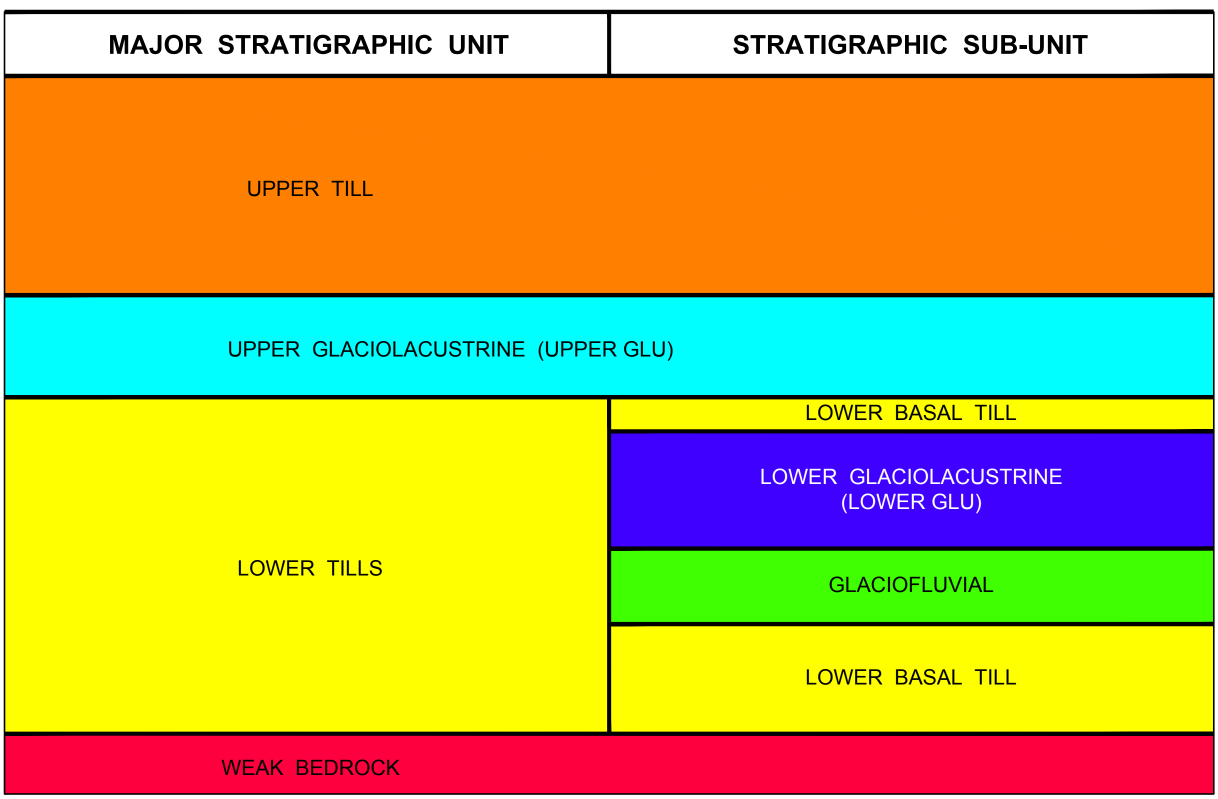
5.2.5 CONTROLLING STRATIGRAPHY

Soils in the breach area are of three main types, all glacially deposited. These include:

- Glaciolacustrine soils (designated GLU) deposited in standing water.
- Glaciofluvial, or streamchannel, deposits.
- Glacial tills produced by glacial transport and reworking.

Appendix D describes the interpreted depositional environment that results in the generalized sequence shown below.

FIGURE 5.2.3: GENERALIZED SOIL STRATIGRAPHY IN BREACH AREA



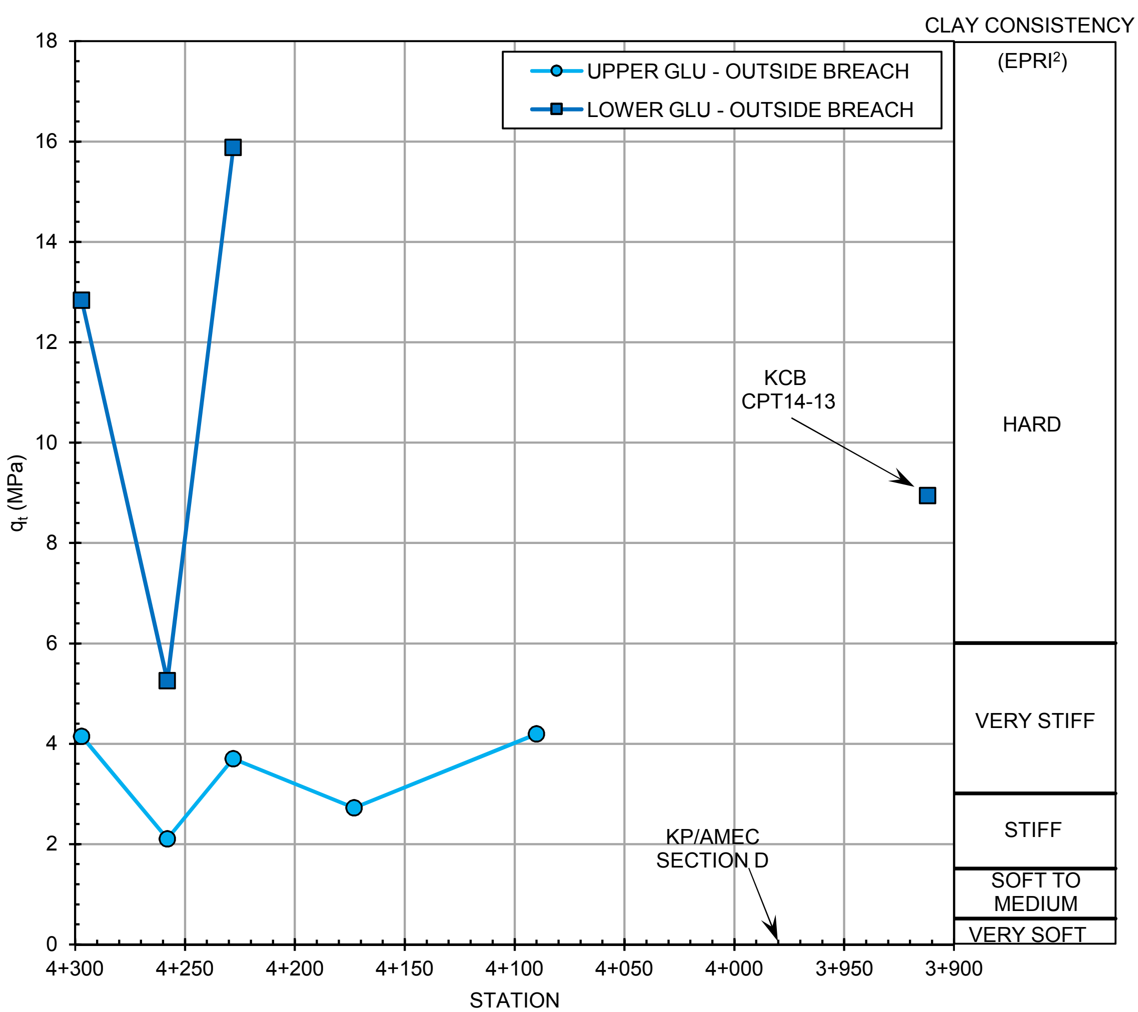
Of special significance are the two glaciolacustrine units designated Upper and Lower GLU, shown in **Figure 5.2.3**, in turquoise and blue, respectively. Both consist of thinly laminated, or varved, silts and clays, and both classify predominantly as low- to high-plasticity clay (CL to CH). They can be distinguished by differences in their pre-failure water content, CPT tip resistance, and overconsolidation ratio (OCR). Establishing these differences requires looking to areas outside the embankment footprint, or those covered by slide debris, in order to eliminate preloading effects. The resulting comparisons therefore reflect initial pre-construction conditions.

5 | Panel Observations

Firstly, the difference in water content is substantial. The average of mean values from individual borings for the Upper GLU is 32%, compared to 24% for the Lower GLU.

Secondly, CPT tip resistance in the two units is distinctly different. **Figure 5.2.4** shows that tip resistance q_t for the Upper GLU is less than one-half of that for the Lower GLU across the breach area. Using q_t as a measure of clay consistency, the Upper GLU classifies as stiff to very stiff, while the Lower GLU classifies as very stiff to hard.

FIGURE 5.2.4: LONGITUDINAL VARIATION IN CPT TIP RESISTANCE



5 | Panel Observations

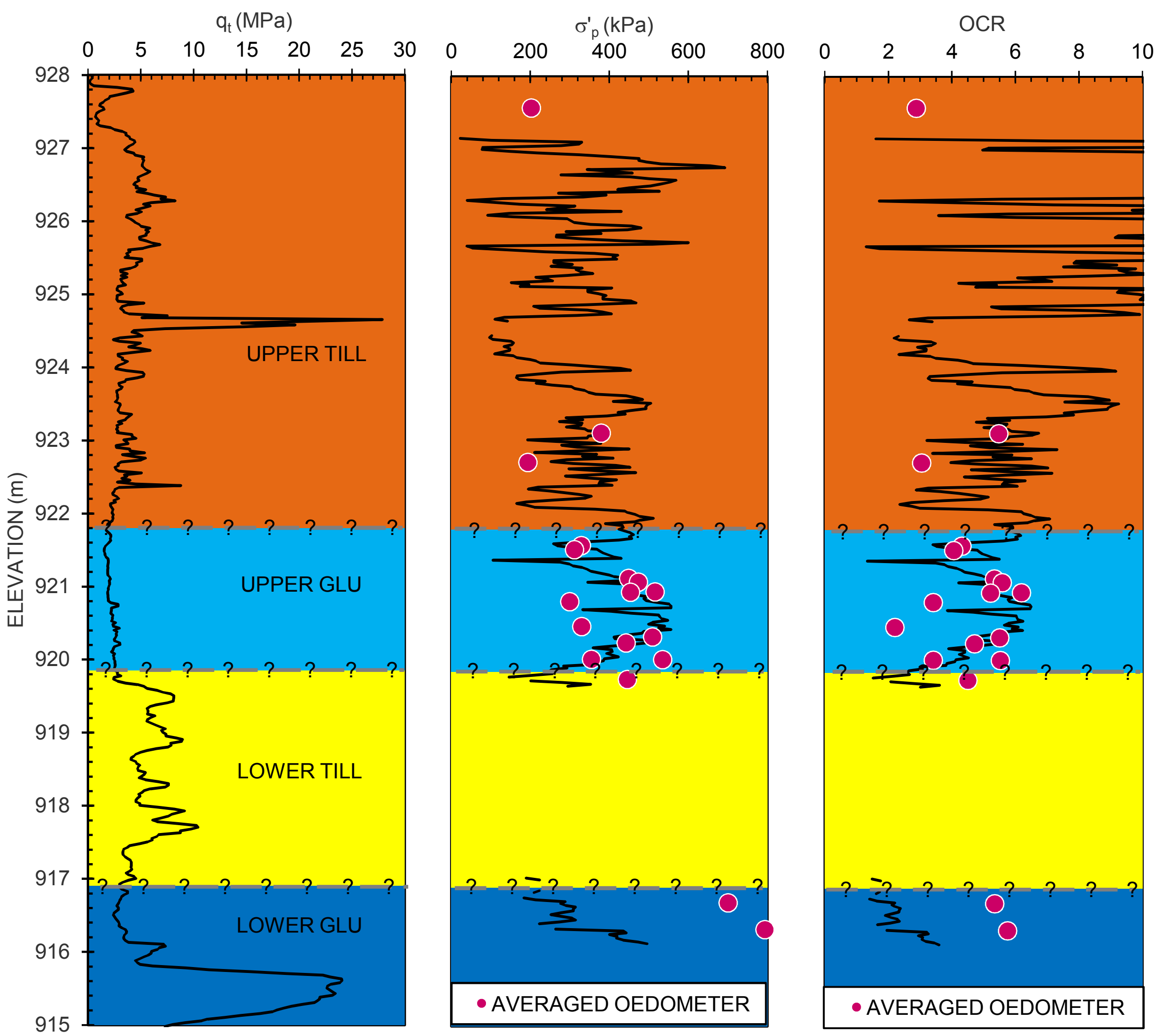
During their depositional history, glaciolacustrine deposits can experience episodes of drying, freezing, glacial overriding, or other factors that consolidate them to varying degrees. The result is to induce an effective preconsolidation pressure, designated σ'_p, that has a substantial influence on undrained strength properties. This effect can also be expressed as the ratio of the preconsolidation pressure to the effective stress in the ground, termed OCR. In general, higher OCR and higher σ'_p correlate with higher undrained strength.

But when the applied stress increases, for example, due to placement of overlying dam fill, OCR decreases. If the higher stress reaches or exceeds σ'_p, the beneficial effects of preconsolidation no longer pertain, and the clay is said to be normally consolidated with OCR = 1.0. Together, the preconsolidation of a clay, the stresses it experiences, and the changes in these stresses are called its stress history, which has a major influence on its undrained strength.

These factors are reflected in the Upper and Lower GLU, where the initial pre-construction σ'_p and OCR are compiled on a composite plot in **Figure 5.2.5** using CPT data from RCPT14-107 and all available oedometer data.

5 | Panel Observations

FIGURE 5.2.5: INITIAL (PRE-CONSTRUCTION) STRESS HISTORY



The continuous plots of σ'_p and OCR adopt published CPT correlations,[2] while the laboratory-derived data points are taken from Appendix E. From laboratory data, the average σ'_p for the Upper and Lower GLU units is 433 kilopascals (kPa) and 748 kPa respectively, with corresponding OCRs of 6.0 and 6.9.

5 | Panel Observations

The differences in properties are summarized in **Table 5.2.1.** Drawing D18 in Appendix D provides further details of the properties.

TABLE 5.2.1 PRE-CONSTRUCTION PROPERTIES OF UPPER AND LOWER GLU IN BREACH AREA

STRATIGRAPHIC UNIT	WATER CONTENT, AVG. AND RANGE	CPT TIP RESISTANCE, q_t AVG., RANGE, AND CONSISTENCY	PRECONSOLIDATION PRESSURE, σ'_p AVG. AND RANGE	OVERCONSOLIDATION RATIO, OCR AVG. AND RANGE
Upper GLU	32% (19 — 53)	3.4 MPa (2.1 — 4.2) (stiff to v. stiff)	433 kPa (312 — 535)	6.0 (4.1 — 7.7)
Lower GLU	24% (19 — 29)	11.4 MPa (5.6 — 16) (v. stiff to hard)	748 kPa (701 — 794)	6.9 (6.7 — 7.2)

Taken together, these properties show that the Upper GLU is the weaker of the two units.

5.2.6 EXTENT AND CONTINUITY OF UPPER GLU

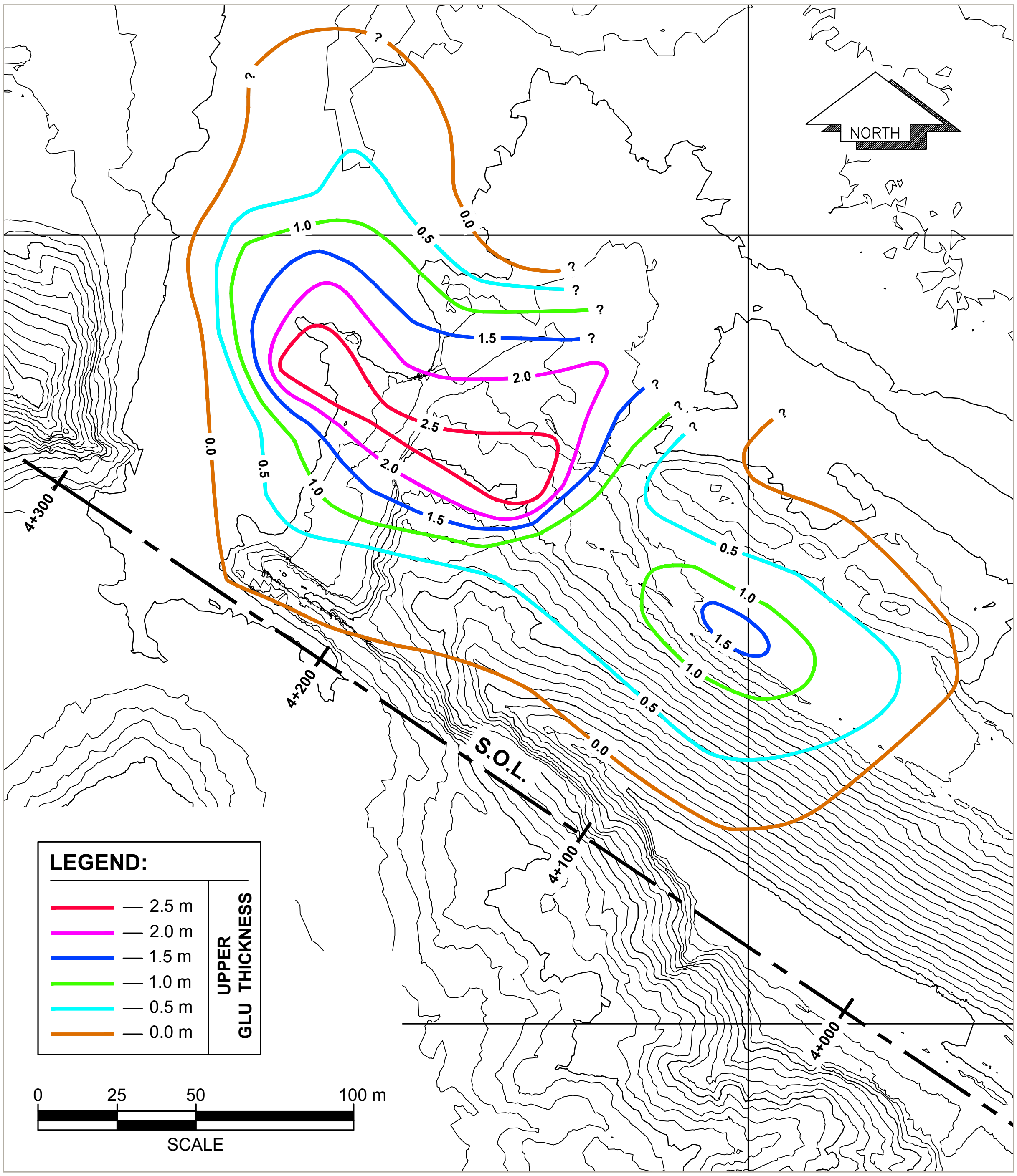
Having targeted the Upper GLU as the controlling stratum, it is of further interest to determine its extent. These results are also highly significant. **Figure 5.2.6** demonstrates that the Upper GLU is not pervasive throughout this entire section of the Perimeter Embankment. But is present in the area beneath the footprint between Sta. 4+050 and Sta. 4+300. Moreover, the greatest thickness directly underlies the remaining slide debris on the right side of the breach, thinning toward the left but still extending across the entire width. The maximum thickness also directly underlies the location of the downstream toe of the embankment at the time of failure.

Having targeted the Upper GLU as the controlling stratum, it is of further interest to determine its extent. These results are also highly significant.

There are smaller-scale variations even within this area. **Figure 5.2.6** shows a localized thickening to the east, just at the limit of the slide from **Figure 5.1.7**.

5 | Panel Observations

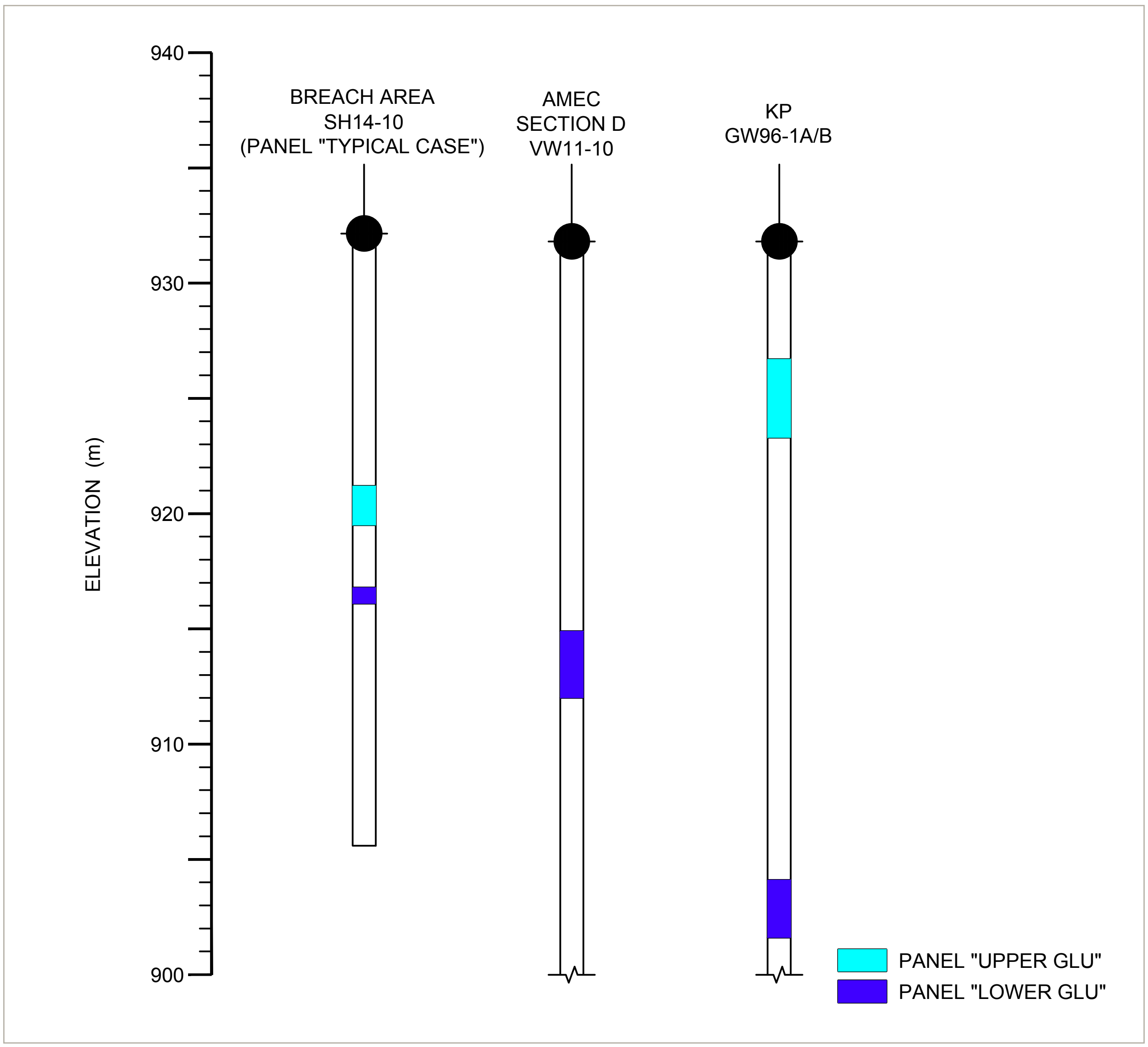
FIGURE 5.2.6: CONTOURS OF UPPER GLU THICKNESS IN BREACH AREA



5 | Panel Observations

Stratigraphic variations on a larger scale are also apparent from **Figure 5.2.7**, which relates the Upper and Lower GLU units at the breach to glaciolacustrine soils elsewhere at boring locations presented previously in **Figure 5.2.2**. The Upper GLU at the breach shows apparent similarities to glaciolacustrine soils at similar elevation in GW96-1A that would be characterized as soft to medium-stiff according to their standard penetration test (SPT) blow count of 6. On the other hand, the uppermost GLU layer encountered in VW11-10 has an average water content of 23%, which corresponds closely to that of the Lower GLU shown in **Table 5.2.1**. Details are provided in Appendix D.

FIGURE 5.2.7: COMPARISON OF GLU UNITS IN BREACH TO OTHER AREAS



5 | Panel Observations

These illustrations of both small-scale and large-scale variation in stratigraphy and properties of the GLU materials serve to highlight the complexity that their depositional environment produced. This degree of geologic complexity discourages attempts at broader generalization beyond the immediate areas where subsurface data have been obtained.

Both small-scale and large-scale variation in stratigraphy and properties of the GLU materials serve to highlight the complexity that their depositional environment produced.

5 | Panel Observations

5.2.7 LOCATION AND CHARACTERISTICS OF FAILURE SURFACE

Section 5.1 previously identified the entry of the failure surface through the surviving core remnant and into the upper foundation till. The subsurface investigations described here reveal the nature and location of the failure surface at depth.

As will be chronicled in section 5.4, the presence of a glacially pre-sheared surface in the dam foundation posed significant uncertainty throughout the design process. This type of pre-shearing, with the residual strength it produces, was also hypothesized as a potential failure mechanism by the Panel in section 4.3.4. Commensurate effort was devoted to detecting the presence of pre-shearing in foundation soils within the breach.

Pre-shearing in stiff, clayey soils manifests as a thin (a few millimetres to a few centimetres) zone with slickensides—shiny surfaces polished by shearing—on both sides of the zone or within it. These surfaces are continuous and traceable between borings, often along bedding. While detailed logging did show some small, discontinuous slickensided surfaces at random orientations, an expected condition in stiff clays, no continuous surfaces common to multiple borings were found. In this respect, the Panel's investigation at the breach corroborated the more general conclusion of the 2011 site investigation.[3]

Even so, the Upper GLU exhibited other signs of shearing inside but not outside the breach. For example, **Figure 5.2.8** compares the Upper GLU for these two locations.

5 | Panel Observations

FIGURE 5.2.8 UPPER GLU (a) INSIDE THE BREACH, (b) OUTSIDE THE BREACH

The thinly laminated, planar varving outside the breach contrasts sharply with the contorted and folded laminations within it. This is consistent with shearing of the Upper GLU having occurred within the breach.

Additionally, CPT tip resistance q_t in the Upper GLU varies systematically. Drawings D19 and D20 in Appendix D show that average q_t inside the breach is only about one-third to two-thirds of that outside of it (inferred sensitivity of 1.0 to 3.0), reflecting the effects of remoulding attributable to shearing. Hence, both visual inspection and CPT data indicate that the failure produced shearing in the Upper GLU. This, together with its less favourable properties summarized in **Table 5.2.1**, identifies the Upper GLU as the location of the failure surface in the analyses to be presented in section 6.

5 | Panel Observations

5.2.8 COMMENTARY

The key findings of the subsurface investigations with regard to the failure mechanism can be summarized as follows:

- The Upper GLU can be distinguished as a distinct foundation unit based on its water content and other properties.
- The failure occurred within varved silts and clays of the Upper GLU.
- There is no indication of pre-shearing in these or other foundation soils.
- Stratigraphic variability reflects a complex geologic environment and depositional history.

Beyond these immediate findings lie other insights that concern characterization of the GLU during the design process. These are summarized below:

- The discontinuous Upper GLU stratum, the seat of the failure, was infelicitously situated at the worst possible place in the dam foundation.
- The type and extent of pre-failure site investigations were not sufficient to detect this stratum or identify its critical nature.
- The strength behaviour of the GLU was misinterpreted.

The first two of these points are evident from the material presented above. The third requires explanation.

From the outset, the stiffness of GLU materials in the Main Embankment foundation was recognized and attributed to overconsolidation. In response to a review comment by the Ministry of Energy and Mines (MEM), KP obtained samples of GLU materials at the Main Embankment in 1995.[4] Commenting on the characteristics of these soils, KP made the following observations:

Two additional Shelby samples were recently collected (May 16, 1995) during the soil investigation survey. These samples were obtained from the glaciolacustrine sediments and have confirmed that the foundation materials consist of dense, overconsolidated materials. In fact, it was extremely difficult to insert the Shelby tubes in the field and it was not possible to extract the undisturbed samples from the tubes in the laboratory... It is unlikely that any significant pore pressure development will occur in these materials during construction of the embankment.

KP concluded that no significant pore pressures would develop, but did not directly relate this to the effective-stress strength properties its stability analyses adopted. This connection was made explicit much later in AMEC's 2011 Geotechnical Site Investigation.[5]

5 | Panel Observations

Among other things, the AMEC report compiled all available data for Liquidity Index (LI) at the Main Embankment, a laboratory parameter that can be correlated to preconsolidation pressure σ'_p. The report noted that a number of GLU samples had low LI values near zero, some of them even negative, pointing again to the overconsolidated condition of the GLU. Elaborating on the strength interpretation this supported, the report went on to say:

Moreover, for heavily overconsolidated soils with high fines contents (such as the GLU) that will shear in an undrained manner due to low hydraulic conductivity, the undrained shear strength will typically exceed the drained shear strength, owing to negative shear-induced pore pressure.

Thus, undrained strength could be disregarded for the GLU, with drained (effective-stress) strength applicable instead.

Review of the AMEC data calls into question the premise of this conclusion. While most of the LI values were indeed low, fully one-third of them were equal to or greater than 0.5. This means that significant portions of the GLU beneath the Main Embankment were not so heavily overconsolidated. From published correlations,[6] the Panel estimates that σ'_p for these higher LI values ranged from about 250 to 575 kPa, quite similar to the range for the Upper GLU at the breach from **Table 5.2.1**. These σ'_p values correspond to an average OCR of only about 3, given the loading conditions of the catalogued samples, insufficiently high to warrant neglecting undrained strength.

But more than this, the assessment did not account for stress history—how these loading conditions varied at different locations beneath the dam or how they would change over time. Stage 7 of the Main Embankment had just been completed at the time of 2011 site investigation. The Panel estimates that normally consolidated conditions (OCR=1) had already been reached beneath the crest of Stage 2 years before and would continue to propagate outward beneath the slope as the dam grew higher. The key factor that went unrecognized was that undrained strength behaviour would unequivocally control for these normally consolidated conditions.

The key factor that went unrecognized was that undrained strength behaviour would unequivocally control for these normally consolidated conditions.

The same effect, equally unrecognized, would occur at the Perimeter Embankment breach section. Normally consolidated conditions, and the governing undrained strength accompanying them, would first develop beneath the crest during Stage 5 and continue to spread thereafter. This would set the stage for much that followed.

5.3 ADVANCED LABORATORY STUDIES

5.3.1 INTRODUCTION

A distinction can be made between routine and advanced laboratory studies. Routine laboratory studies are performed as part of the description and classification of materials encountered in a site characterization study. Routine laboratory studies undertaken in this investigation have been reported as part of the description of materials identified in the site characterization investigation (see Appendix D). Advanced laboratory studies are undertaken to aid in the explanation of the physical response of a soil to loading. Important responses are the reduction in volume of a soil when loaded, reflected by consolidation testing, and the ultimate resistance of a soil specimen, as measured by a variety of shear strength tests.

5.3.2 SAMPLING

The joint site investigation, summarized in section 5.2, concentrated on the ground conditions adjacent to the breach that would have been affected by the ground movements. The Panel-directed investigation concentrated on the ground conditions adjacent to the disturbed zone in order to provide the opportunity to inspect soil conditions that would not have been affected by the ground movements. Obtaining undisturbed samples for both inspection and advanced laboratory studies was an integral objective of this investigation.

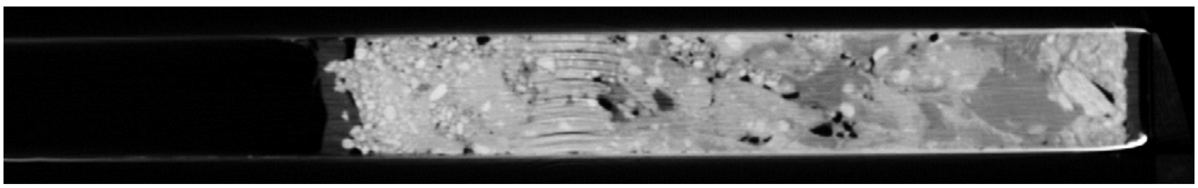
Obtaining undisturbed samples requires pushing a thin-walled sampler into the ground. Given the conditions encountered, this was not a straightforward exercise. The till contains numerous rocks, and even the fine-grained glaciolacustrine (GLU) deposits contain gravel-sized pieces, most likely deposited during melt of ice rafts.

The inventory of samples that were potentially useful for undisturbed sample testing is tabulated in Appendix E. All samples were subject to scanning at FP Innovations at the University of British Columbia (UBC). This facility can undertake both X-ray and CT scanning on large items. Both digital radiography and CT scans were completed on all sample tubes. Observation of internal disturbance, voids or natural structure aided in the quality control. The horizontal CT scans ultimately proved best to determine complex interlayering and to detect voids. **Figure 5.3.1** displays a sample of till (MR14-104-SA8) that exhibits significant sample disturbance, together with a sample of the GLU (MR14-106E-SA3) that shows internal structure with minimal disturbance. Scans performed on the inventory of samples obtained are included in Appendix E.

WaterLegacy PTM Objections
Exhibit 6

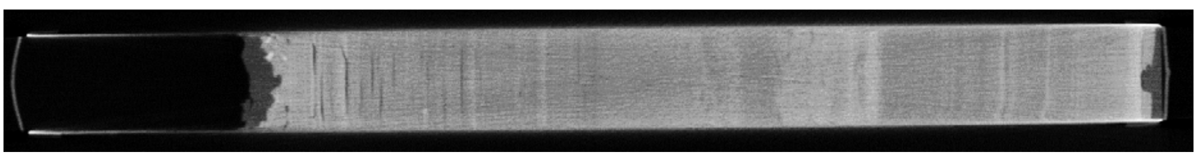
5 | Panel Observations

FIGURE 5.3.1: CT SCAN/TILL/GLU



TILL SAMPLE (MR14-104-SA8)

DEPTH: 11.4 TO 12.0 M / EL. 920.3 TO 919.7 M



UPPER GLU SAMPLE (MR14-106E-SA3)

DEPTH: 8.2 TO 8.8 M / EL. 920.5 TO 919.9 M

5 | Panel Observations

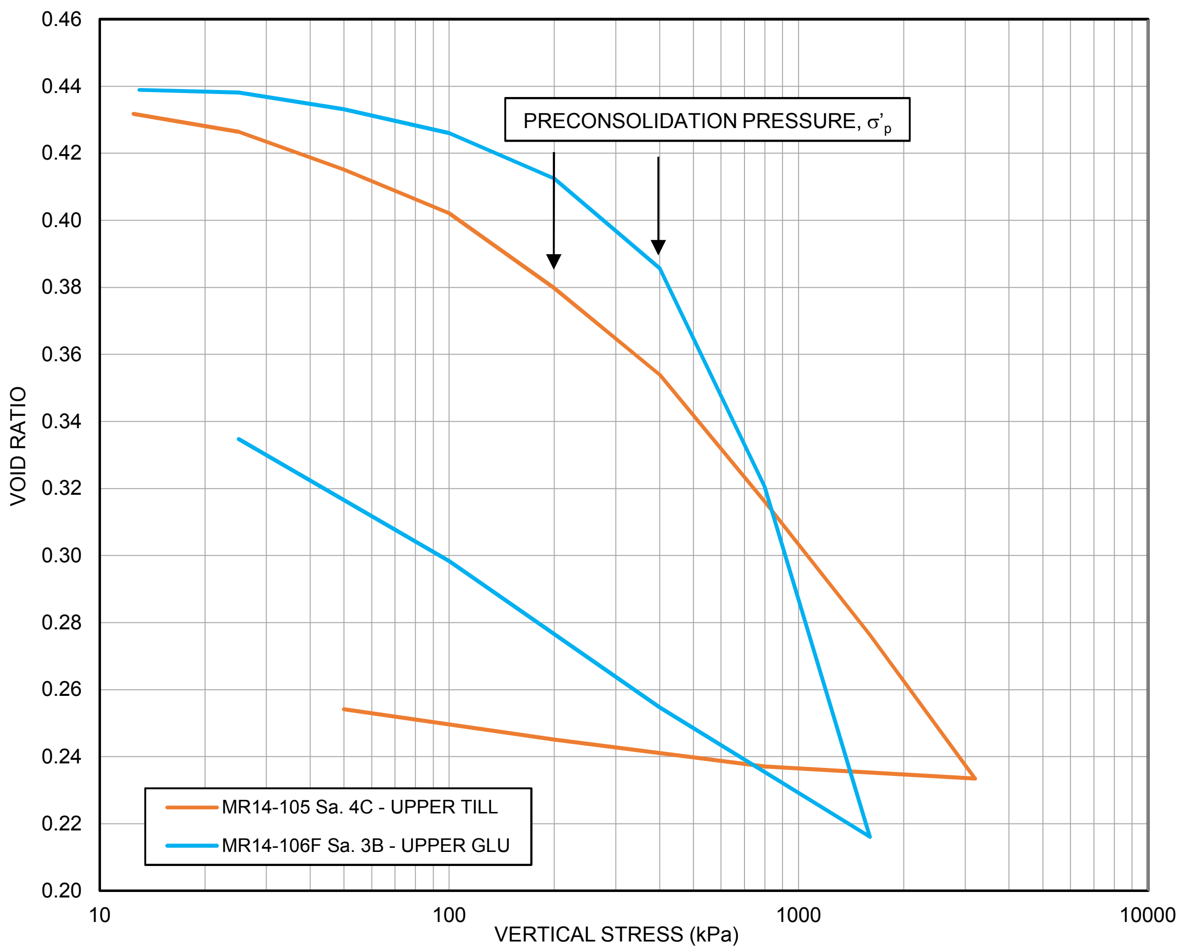
5.3.3 OEDOMETER TESTS

Oedometer tests are used to study the reduction in void ratio (porosity), with applied load simulating the construction of the embankment in stages. The change in curvature of the settlement response provides a base for estimating the preconsolidation pressure of the deposit, which is the maximum pressure experienced by the deposit in its geological past. The technique is illustrated in **Figure 5.3.2** for both a till specimen and a GLU specimen. Till is fundamentally less compressible than the GLU, and the technique to estimate preconsolidation stress has greater uncertainty. The data reveal that these deposits are not highly overconsolidated and that the pressure to be applied by the embankment will exceed the preconsolidation pressure, creating normally consolidated conditions. Normally consolidated conditions are conducive for the soil to behave in a contractive manner when subjected to both vertical pressure and shear.

The data reveal that these deposits are not highly overconsolidated and that the pressure to be applied by the embankment will exceed the preconsolidation pressure, creating normally consolidated conditions.

5 | Panel Observations

FIGURE 5.3.2: PRECONSOLIDATION STRESS EFFECT FOR BOTH TILL AND GLU

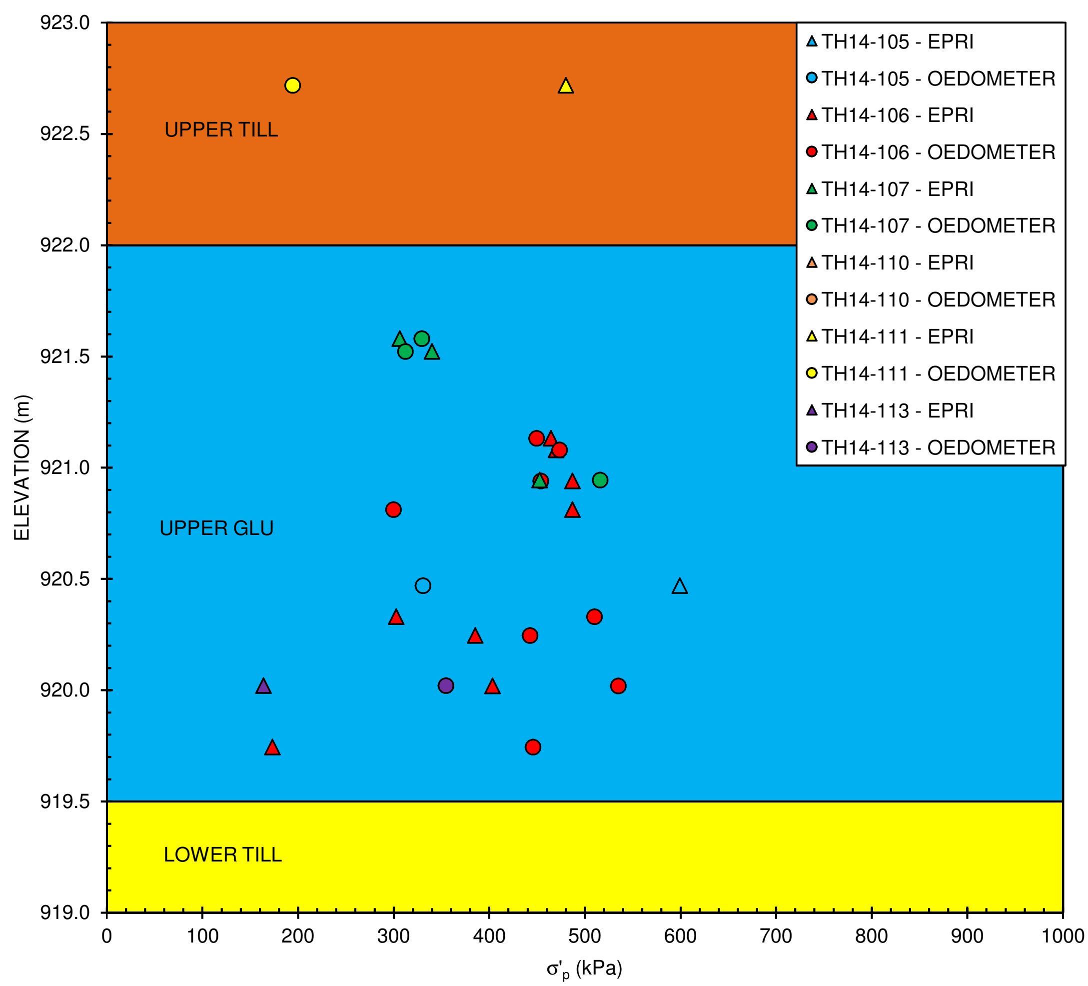


5 | Panel Observations

Preconsolidation pressure can also be inferred from the CPT testing conducted as part of the Panel's site investigation. Again, only modest preconsolidation stresses have been determined. A comparison between the results obtained from the field tests with those obtained from the oedometer tests is shown in **Figure 5.3.3**, and the agreement is acceptable. As the embankment was raised to a stress level beyond the preconsolidation stresses, the underlying GLU reverted to normally consolidated behaviour.

As the embankment was raised to a stress level beyond the preconsolidation stresses, the underlying GLU reverted to normally consolidated behaviour.

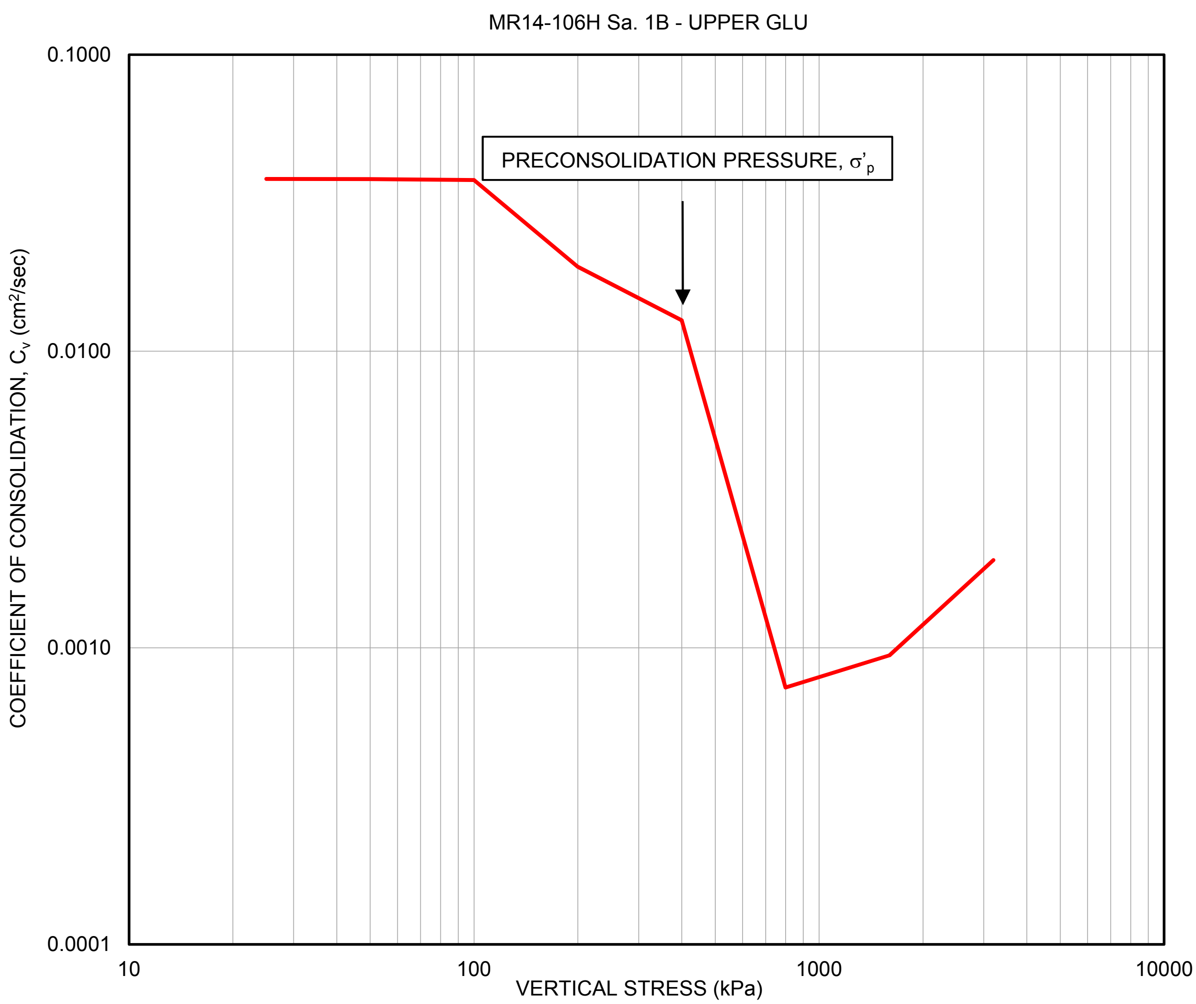
FIGURE 5.3.3: PRECONSOLIDATION PRESSURE WITH ELEVATION



5 | Panel Observations

The data from oedometer tests are presented in Appendix E, including information on the coefficient of consolidation that reflects the rate of pore pressure dissipation on loading. **Figure 5.3.4** provides an example of this response. The significant reduction in this value in the GLU at pressures in excess of the preconsolidation stress is noteworthy.

FIGURE 5.3.4: VARIATION OF COEFFICIENT OF CONSOLIDATION WITH APPLIED VERTICAL STRESS



5 | Panel Observations

5.3.4 DIRECT SIMPLE SHEAR (DSS) TESTS

The subsurface characterization has inferred a sub-horizontal shear zone at about El. 920 m. The strength along this zone is best evaluated by DSS tests, which provide the ratio of undrained strength S_u to effective vertical consolidation stress σ_V', or simply the undrained strength ratio. Tests on specimens from the GLU unit that reflect the shear zone at about El. 920–921 m are particularly relevant to the stability analyses that are discussed in section 6. Accordingly, the test program has been extensive, varying initial confining stress and initial shear stress. Testing with an initial shear stress (i.e., stress bias) is intended to explore the influence of a stage-constructed embankment that induces shear stresses in the ground prior to failure.

Another important feature exhibited by this test program on GLU specimens is a decline in resistance following its peak. This is called strain weakening. An example of a test exhibiting strain weakening is shown in **Figure 5.3.5**. As will be discussed, the presence of strain weakening contributes to understanding of the sudden nature of the breach mechanism. **Table 5.3.1** summarizes test characteristics and results from the DSS test program. Complete test results, with a brief description of test methodology, are presented in Appendix E.

5 | Panel Observations

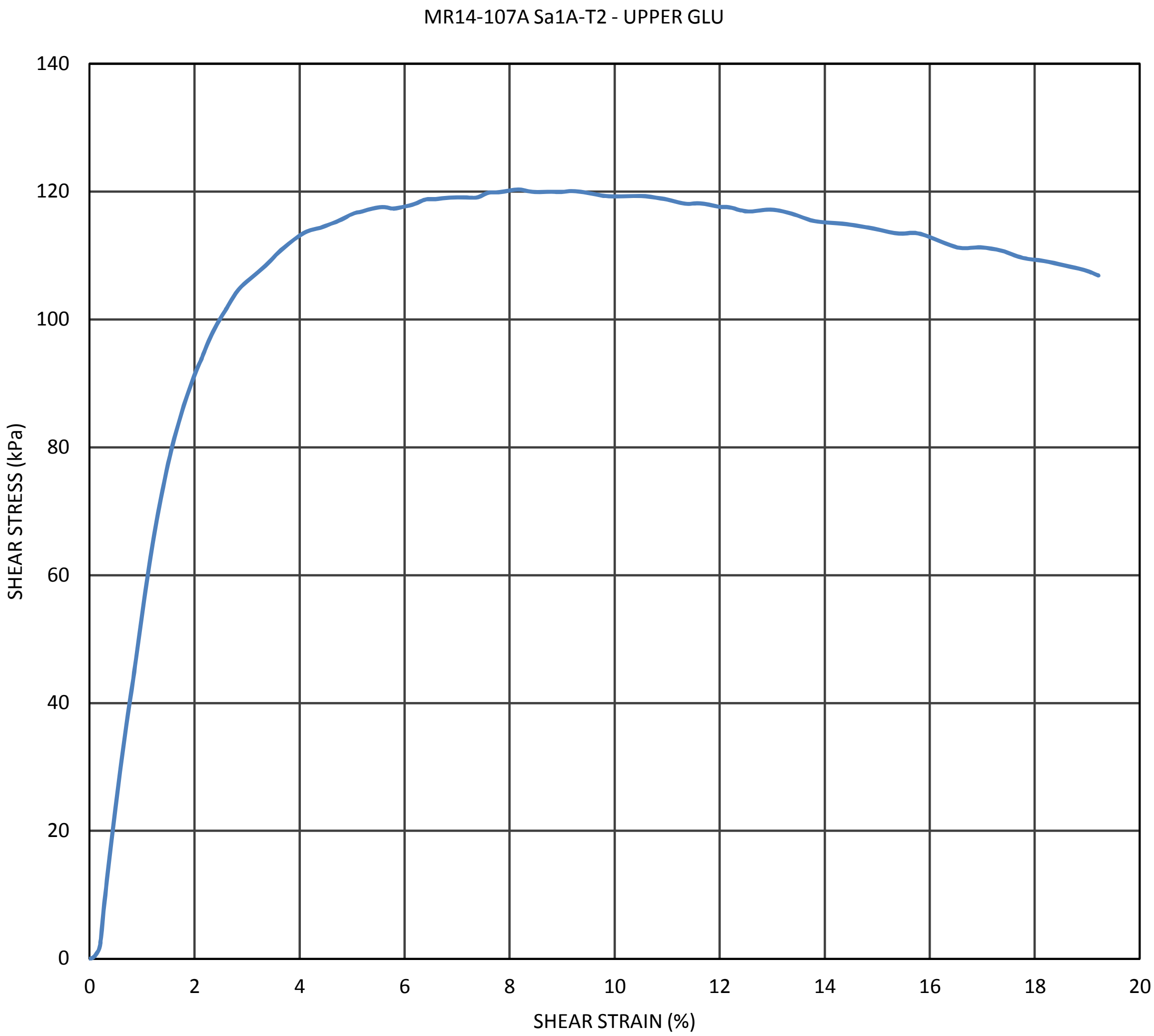
TABLE 5.3.1: SUMMARY OF DIRECT SIMPLE SHEAR (DSS) TEST RESULTS

SAMPLE	ELEVATION (m)	INFERRED PANEL SOIL UNIT	WATER CONTENT (%)	PLASTICITY INDEX	VERTICAL STRESS (kPa)	SHEAR BIAS	PEAK UNDRAINED STRENGTH RATIO
14-106A Sa1C-T1		UPPER GLU	43	31	600	0%	0.22
14-106A Sa1C-T2	921.1	UPPER GLU	37	31	600	10%	0.23
14-106A Sa1C-T3	921.1	UPPER GLU	38	31	600	20%	0.26
14-106A Sa1C-T4	921.1	UPPER GLU	33	31	300	20%	0.28
14-106C Sa1B-T1	921.2	UPPER GLU	44	33	600	30%	N/A
14-106C Sa1B-T2	921.2	UPPER GLU	43	33	600	25%	0.27
14-106C Sa1B-T3	921.2	UPPER GLU	39	33	600	10%	0.21
14-106G SA2B-T1	920.9	UPPER GLU	44	21	600	10%	0.21
14-106G SaB-T2	920.6	UPPER GLU	38	21	600	20%	0.26
14-107 Sa6C-T1	921.5	UPPER GLU	44	23	300	10%	0.27
14-107 Sa6C-T2	921.5	UPPER GLU	43	23	300	10%	0.25
14-107A Sa1A-T1	920.9	UPPER GLU	43	34	600	0%	0.21
14-107A Sa1A-T2	921.0	UPPER GLU	42	34	600	0%	0.20
14-107A Sa7	916.3	LOWER GLU	26	15	600	0%	0.30
14-109 Sa6B	916.6	LOWER GLU	22	13	300	10%	0.42
14-110 Sa6C	916.3	LOWER GLU	21	15	300	10%	0.27
14-113 Sa4B	922.9	UPPER TILL	13	7	300	10%	0.43

Average Peak Undrained Strength Ratio in Upper GLU	(no shear bias)	0.21
	(10% shear bias)	0.23
	(≥ = 20% shear bias)	0.27
	overall	0.24

5 | Panel Observations

FIGURE 5.3.5: DSS TEST: GLU WITH STRAIN WEAKENING



5 | Panel Observations

5.3.5 TRIAXIAL COMPRESSION TESTS

Triaxial compression tests with pore pressure measurements have also been conducted, in part for the record, and in part for use in stability analysis. The triaxial test data on till, together with the results from in situ pressuremeter tests, were used to inform the judgment of the Panel on an appropriate value to be used in the stability analyses.

Details of all triaxial tests are tabulated and presented in Appendix E.

5.3.6 DIRECT SHEAR TEST

While not used directly on any of its analyses, the Panel undertook a direct shear test on a pre-cut specimen of the GLU. This was primarily for the record, but afforded an opportunity for comparison with magnitudes adopted in some phases of the design. The Panel's measured residual strength of 16 degrees is at the lower end of the range used by others. The data are found in Appendix E.

5.3.7 DESIGN BASIS TESTING

The design of the Perimeter Embankment did not rely on any deep sampling of its foundation. Hence, no undisturbed samples were obtained, and no advanced laboratory tests were performed to provide data for purposes of comparison.

5.3.8 JOINT INVESTIGATION

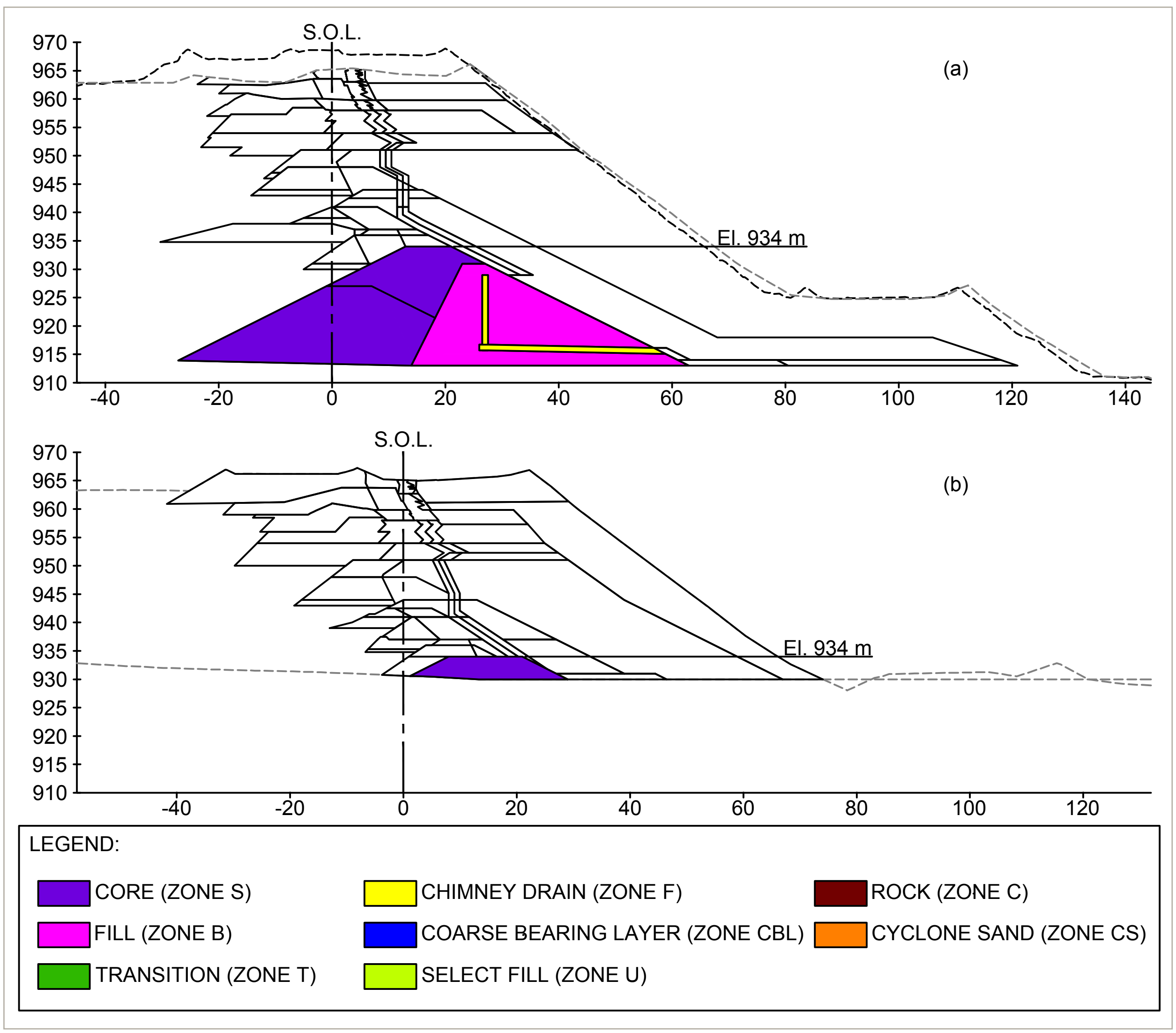
Advanced laboratory studies were also performed on samples procured during the joint site investigation. The tests were not performed under the direction of the Panel, but are also included in a separate identifiable section within Appendix E.

5.4 DESIGN, CONSTRUCTION AND OPERATION

This section describes the historical and sequential development of the Mount Polley Tailings Dam. The Main Embankment is included here along with the Perimeter Embankment to explain salient features and milestones related to design, construction and operation. The dam was developed in stages designated 1 through 9 that are treated in turn in the following discussion. At each stage, as-built cross-sections for the Main Embankment and for the Perimeter Embankment at the breach location are used to portray the dam's progressive expansion.

5.4.1 STAGE 1: 1997 — 1998

FIGURE 5.4.1: STAGE 1 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

Design of the Main Embankment in May 1995 [7] by KP established the direction for subsequent events. The overall plan incorporated dam raises to El. 960, of which Stage 1 would be the first, as illustrated in **Figure 5.4.1**. With planned raising by the "modified centreline" method, [8] the ultimate dam would rely on deposited tailings to provide structural support for the core. Fill would consist primarily of glacial till borrow soils, with sand tailings obtained by cycloning placed upstream of the core. The setting out line (S.O.L) provided the reference for dimensioning the dam's fill zones and for stationing along its length.

Seismic criteria were based on a "low" consequence classification as defined by the Canadian Dam Association (CDA). The minimum factor of safety (FS) for the downstream dam slope was taken as 1.3 during impoundment operation and 1.5 at closure, design criteria that remained in effect for all subsequent raises. For the 2H:1V Stage 1 downstream slope, an effective-stress analysis (ESA) showed FS = 1.43, thereby satisfying the operational requirement.

Glaciolacustrine (GLU) fine sands, silts and clays were recognized from the outset to be present in the Main Embankment foundation. They were described as "typically dense to very dense and have been heavily overconsolidated by glaciers," with two samples confirming that they consisted of "stiff, overconsolidated materials." [9] In a crucial interpretation of their behaviour that would be relied upon throughout, a Ministry of Energy and Mines (MEM) query prompted KP to respond that "it is unlikely that any significant pore pressure development will occur in these materials during construction of the embankment." [10]

Refinement of the Stage 1 design and its component Stages 1A and 1B continued as construction approached. With encouragement from MEM's regulatory precursor, the Ministry of Employment and Investment, a narrow (1 m wide) chimney drain was added, [11] and four relief wells were installed in the foundation of the Main Embankment to reduce uplift pressures acting on GLU layers. [12]

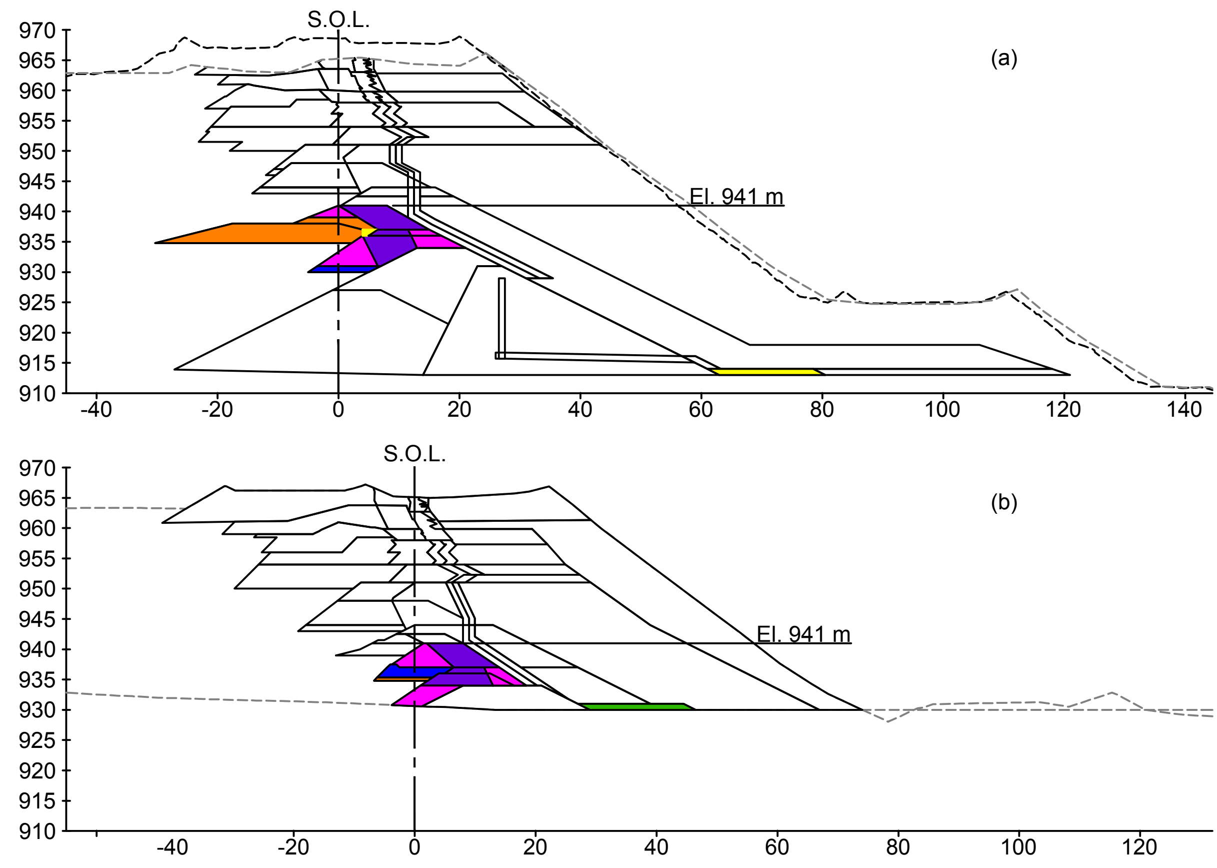
In addition, the detailed Stage 1 design included a small dam only a few metres high to close off a topographic depression west of the Main Embankment. Designated the Perimeter Embankment and shown in **Figure 5.4.1(b)**, it would grow with subsequent stages to itself become a substantial structure contiguous with the Main Embankment. It would also host the site of the breach.

Construction of Stage 1 was completed in March 1997. Glacial till (Zone S and Zone B) was sourced from borrow excavations within the impoundment interior. The chimney drain materials (Zone F) were obtained by crushing, as would remain the case for subsequent raises. Both materials were subject to Construction Quality Assurance (CQA) testing. Vibrating wire piezometers were installed in both the embankment fill and foundation, with four of the six foundation instruments indicating elevated pressures. In response, a new operational stability criterion was established—an allowable ESA factor of safety of 1.1 at a trigger (action) level of 6 m of measured pressure head above the ground surface. [13, 14]

5 | Panel Observations

5.4.2 STAGE 2: 1998 — 2000

FIGURE 5.4.2: STAGE 2 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

Stage 2 was designed to be the first "modified centreline" raise. In the design, the core (Zone S) and chimney drain (Zone F) were extended upward, while adding a new zone of what was intended to be mine waste rock (Zone C) on the downstream slope and outward as a berm along the Main Embankment. [15] Another new feature for the Main Embankment was a longitudinal drain, designated the "upstream toe drain," on the upstream side of the core near the crest of the raise. Its purpose was to allow drainage of the deposited tailings and reduce the embankment phreatic surface. An additional seven relief wells [16] and a relief trench were also included to reduce elevated foundation pore pressures. For the design configuration of the Main Embankment, FS = 1.67 was computed for the downstream slope, exceeding the minimum required value of 1.3. [17]

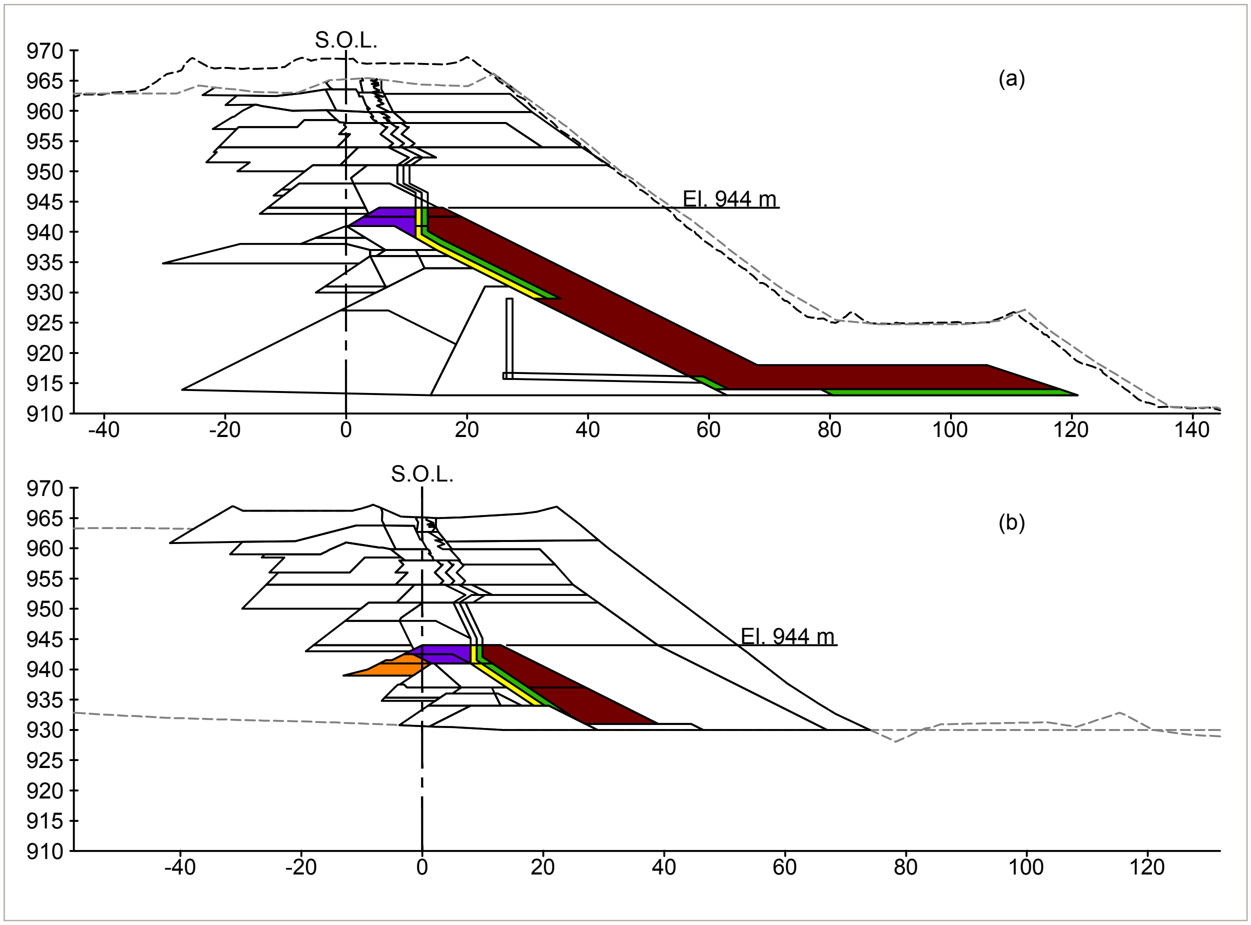
The as-built configuration of the Stage 2 Main Embankment shown in **Figure 5.4.2(a)** differed from the design in several important respects. The intended Zone C mine waste fill was not added to the downstream slope, and the berm along the toe was not constructed. Rather than adhering to a "centreline" configuration, raise 2 utilized entirely "upstream" construction. [18] The same conditions prevailed for the Perimeter Embankment shown in **Figure 5.4.2(b)**. These as-built conditions were never reconciled with the Stage 2 stability analyses, which had been predicated on the original design configuration.

Operational trials and test fills established the feasibility of using cyclone sand underflow upstream of the core (Zone CS), and Stage 2 was the first to do so. A limited trial zone of cyclone sand would remain in the downstream shell of the Perimeter Embankment at design Section D, but cycloning would later be abandoned for both operational and economic reasons. [19, 20]

In other operational matters, problems with the tailings pipeline system produced difficulties in maintaining the required tailings beach, with water directly contacting the embankments in some places. [21]

5.4.3 STAGE 3: 2000 — 2001

FIGURE 5.4.3: STAGE 3 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

As Stage 2 was being constructed, efforts were underway to select materials for the upcoming Stage 3 and the remainder of the dam. A series of design studies in 1999 and 2000 developed a variety of configurations and options using cyclone sand [22, 23] as well as a rockfill alternative. [24] Various combinations were considered for the Main Embankment, the Perimeter Embankment, and the newly added South Embankment that would confine the third side of the impoundment beginning with Stage 3.

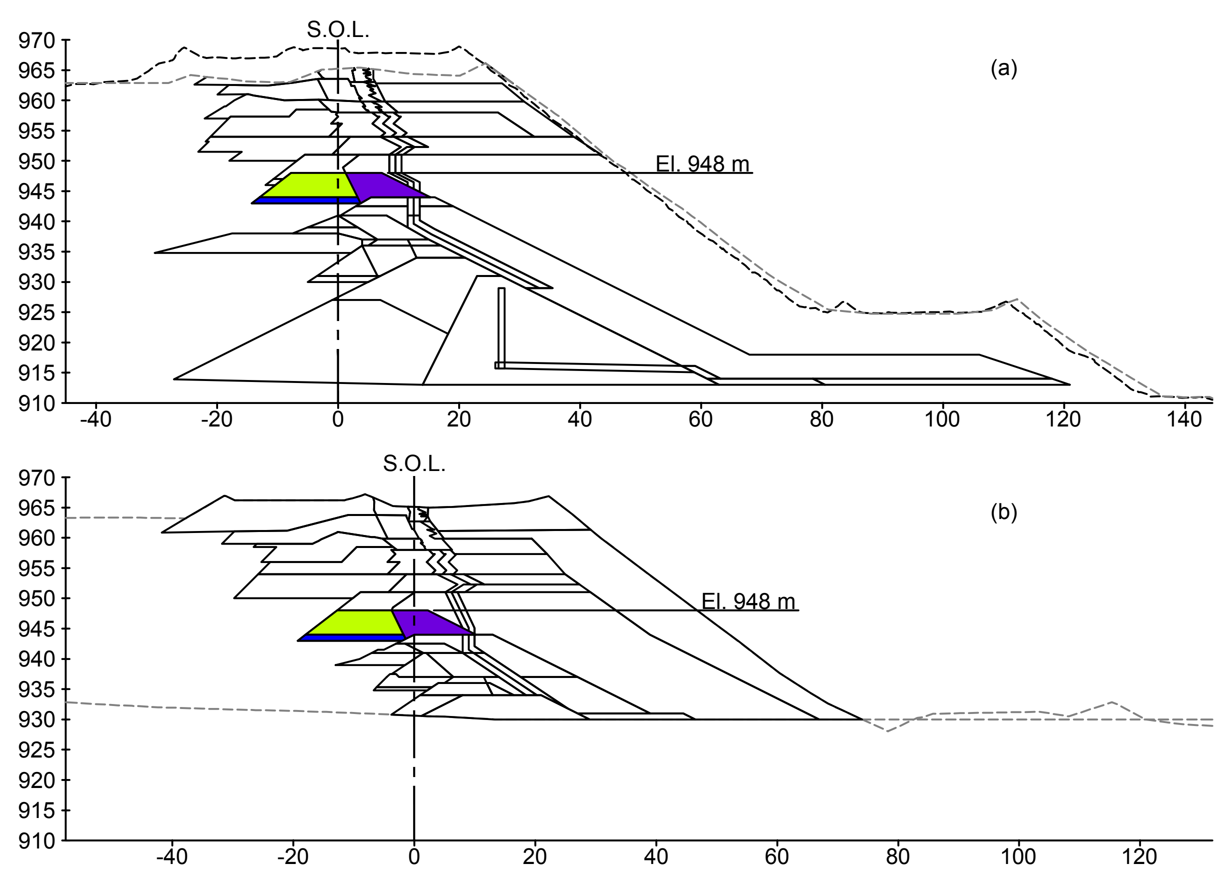
In May 2000, MPMC requested approval from MEM for a Stage 3 design using only cyclone sand for the Perimeter Embankment, with the Main Embankment raised using rockfill and the South Embankment with glacial till. [25] This was changed, however, in April 2001, when MPMC requested MEM approval for yet a different Stage 3 design using rockfill for the downstream Zone C in all three embankments. As shown by the as-built configuration in Figure 5.4.3, this plan was ultimately adopted for Stage 3 using rockfill sourced from a quarry. [26]

Despite the convoluted nature of the Stage 3 design process, an important milestone was that the Observational Method was formally invoked as the basis for design. [27] Thenceforward, each incremental raise was to be continually re-evaluated during operations, based on measured data from the piezometers and two inclinometers installed in July 2001. Putting this into effect, however, would have to wait. Not long thereafter, Mine operations were suspended for economic reasons on October 13, 2001. [28]

5 | Panel Observations

5.4.4 STAGE 4: 2005 — 2006

FIGURE 5.4.4: STAGE 4 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

After a hiatus of over 3 years, Mine operations resumed in February 2005. Design of the Stage 4 raise called for a small cap on the Stage 3 crest extending over the tailings in an "upstream" configuration, together with Zone C rockfill on the downstream slope. Also included in the design was a rockfill buttress on the downstream slope of the Main Embankment to increase the factor of safety to 1.5 in anticipation of closure requirements.[29]

As illustrated in **Figure 5.4.4**, only the cap was constructed in Stage 4 without any additional rockfill on the downstream slope, resulting in another "upstream"-type raise.[30] In constructing this raise, trial programs pioneered the use of hydraulic-cell deposition of tailings for the upstream Zone U, a practice that continued throughout construction.

Separately, operational problems in maintaining the required tailings beach continued, with water directly against the embankment in several areas.[31]

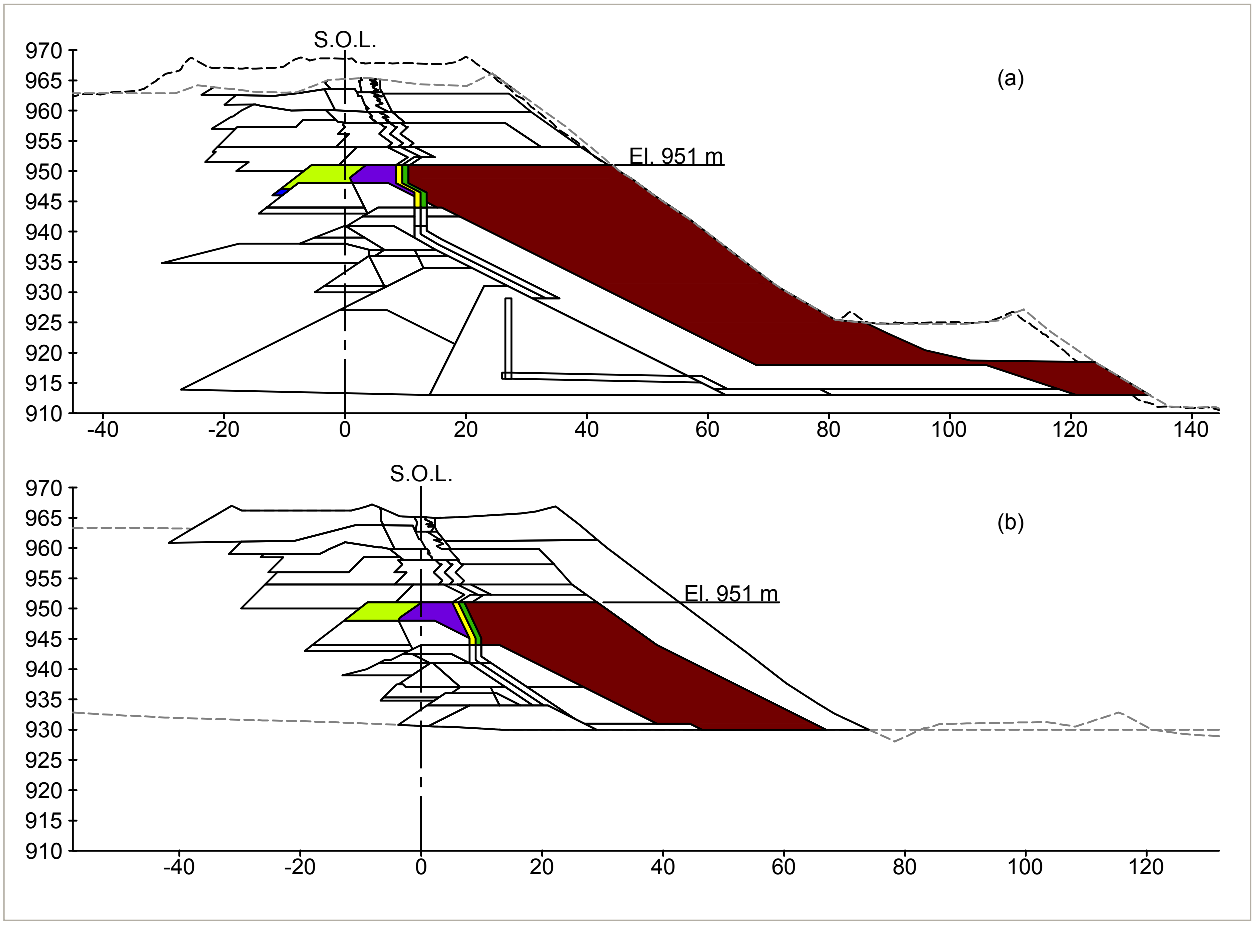
Renewed operation brought renewed queries from MEM concerning the glaciolacustrine foundation materials. One concerned the characteristics and effects on dam stability of softer GLU deposits at groundwater well GW96-1A downstream from the Perimeter Embankment.[32] In response, KP cited borrow area test pits and auger borings as confirming that "the glaciolacustrine deposit encountered in GW96-1A is a discontinuous unit and will not adversely affect the dam stability."[33]

The breach subsequently occurred 300 m due west of GW96-1A.

5 | Panel Observations

5.4.5 STAGE 5: 2006 — 2007

FIGURE 5.4.5: STAGE 5 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

The Stage 5 design once again incorporated the downstream Zone C rockfill that had been deferred in previous stages, and this time it was built. But since the material would now be sourced from mine waste rather than quarried, mine production and delivery had to be accommodated.[34] Due to related restrictions, it was planned to place the Zone C outslope to an "interim" 1.4H:1V inclination—rather than the design basis 2.0H:1V—as a temporary expedient until mine waste delivery could catch up with construction. The steeper slope would be expanded and flattened to 2.0H:1V "once the embankments have reached the Stage 5 design elevation."[35] An ESA factor of safety of 1.5 was reported for the steeper interim slopes of the Main Embankment and 1.9 for the Perimeter Embankment.

It was planned to place the Zone C outslope to an "interim" 1.4H:1V inclination—rather than the design basis 2.0H:1V—as a temporary expedient until mine waste delivery could catch up with construction.

Stage 5 construction proceeded from Stage 4 in a continuous, uninterrupted campaign and was completed in November 2007. But instead of rectifying the interim steep slopes at this time as had been intended, such measures were left to future stages of embankment raising.[36]

Stage 5 saw the first substantial enlargement of the Perimeter Embankment, with widening of the crest and expansion of the downstream Zone C rockfill as shown in **Figure 5.4.5(b)**. At the same time, an upstream toe drain was added to complement the companion drain already installed at the Main Embankment.

Operationally, chronic problems with maintaining the tailings beach continued, with procurement of enough tailings pipe to traverse the entire embankment perimeter now the anticipated solution.[37]

The year 2006 marked the 10-year interval for the mandatory third-party Dam Safety Review (DSR), which was prepared by AMEC.[38] The most salient aspects of this report concern its assessment of foundation strength and related dam stability. Shear failure of the dam slope, including failure through the foundation, was first on a list of potential failure modes applicable to the Mount Polley dam in relation to "excessive loading at or near the crest or a weakness in the foundation." Noting the apparent overconsolidation of the glaciolacustrine materials, the report identified two conditions of particular interest: the possible presence of pre-sheared planes of weakness, and the potential for "brittle" response involving strength loss at small strains. The DSR contained no mention of the behaviour of foundation materials in undrained shear.

The Dam Safety Review contained no mention of the behaviour of foundation materials in undrained shear.

5 | Panel Observations

The DSR also remarked on the lack of a tailings placement strategy that had impeded systematic development of a tailings beach for so long, calling lack of such a beach a "deficiency" and noting that the dam had not been designed as a water dam.

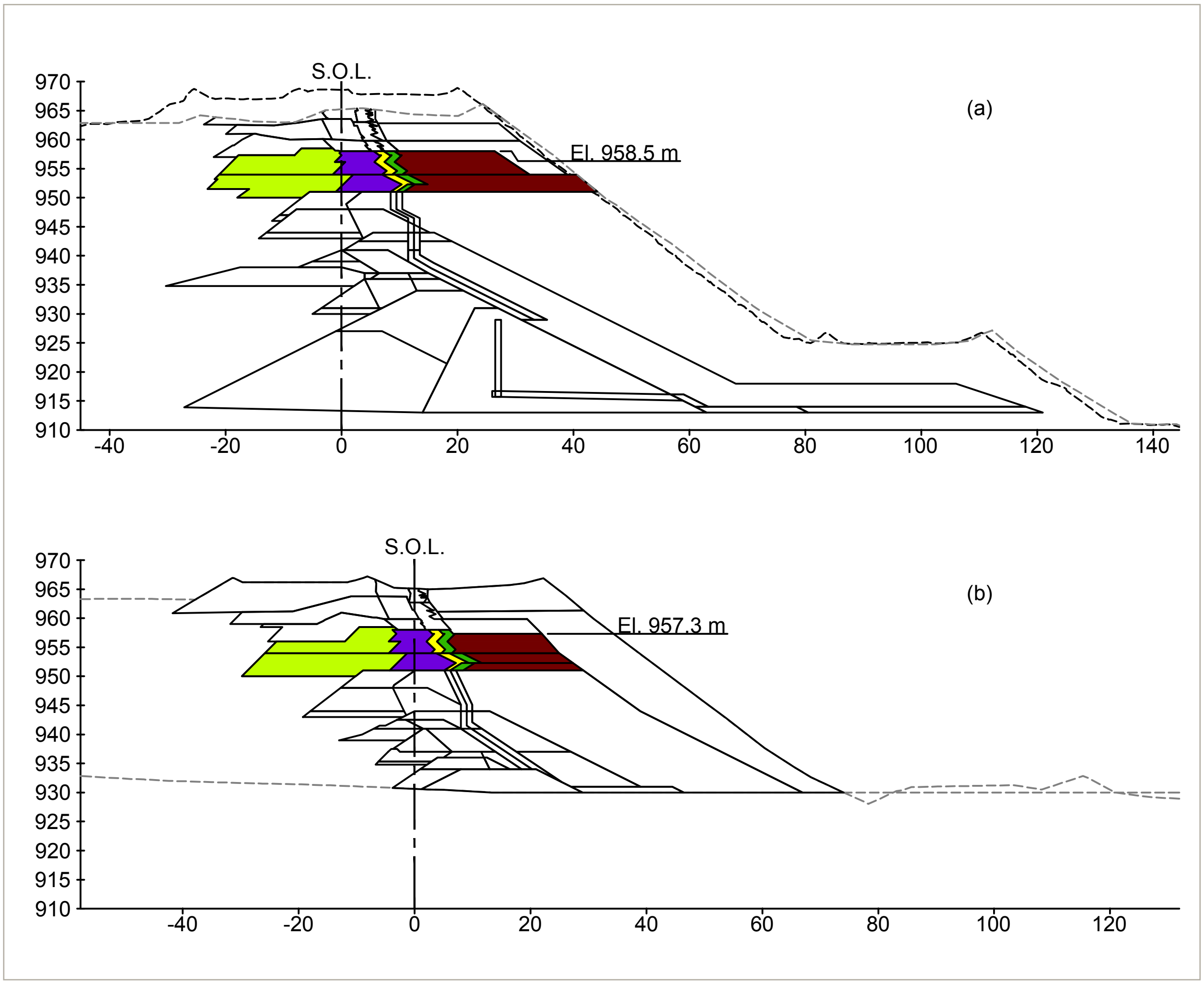
Shortly after the DSR was submitted, at MPMC's request, AMEC produced a follow-up report that reviewed several possible optimization measures for the TSF.[39] One measure was to reduce the width of the core to as little as 3 m to 4 m. Another was to eliminate the uppermost 1 m of the dam core, since this part of the crest "only provides freeboard."

The optimization report also questioned the need for the Main Embankment buttress first proposed for Stage 4 and partially constructed for Stage 5. It concluded that foundation strengths used previously would result in adequate stability without a buttress. The only proviso was the potential for pre-sheared planes of weakness in the foundation, a question that remained outstanding from the DSR.

With the water balance "fine tuned to an accuracy that is in the range of centimeters" in terms of impoundment water elevation, the report proposed that the wave runup allowance, and therefore freeboard requirements, could be reduced. Remarking on beach development, it further stated that unless water was deep enough to affect stability of the Zone U tailings, there was "no rush" in developing a beach along the Main Embankment to correct the deficiency identified in the DSR.

5.4.6 STAGE 6: 2007 — 2011

FIGURE 5.4.6: STAGE 6 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

The Stage 6 design for the Main Embankment incorporated two components: an additional 7 m of fill on the crest, and a Zone C rockfill buttress at the downstream toe. The Zone S core was reduced from its former 8 m width to 5 m on the basis of the effectiveness of the upstream toe drains in lowering the phreatic surface and gradients within the core.[40] Stage 6 also introduced the practice of raising the Zone S core, the thin Zone F filter, and the equally thin Zone T transition in an intricate zigzag configuration.

The Main Embankment buttress, first included in the Stage 4 design but never fully constructed, was an outgrowth of two factors. First was the effect on stability of the "interim" 1.4H:1V slopes that had persisted since Stage 5. Second were the foundation strength interpretations put forward in the DSR. Stage 6 stability analyses adopted an estimated residual strength of 24° for the GLU foundation materials at the Main Embankment to account for the possible presence of pre-shearing. The resulting buttress produced an ESA factor of safety of 1.4, satisfying the FS = 1.3 design requirement for operation.

But once again, the Stage 6 buttress was not constructed as designed, turning out to be about 5 m below its design height and short of its design extent.

The Stage 6 design sought to accommodate the limited mine waste delivery rates experienced in Stage 5—and the consequent slope oversteepening—by extending construction over a 2-year period. Even so, the calculated FS = 1.4 for the Stage 6 Main Embankment indicated that the buttress would need to continue being raised in future dam stages, requiring more material. To make matters worse, KP noted that only non-reactive mine waste could be used, further constraining available quantities and confirming buttress construction as a continuing proposition. But once again, the Stage 6 buttress was not constructed as designed, turning out to be about 5 m below its design height and short of its design extent.[41]

None of these buttressing considerations pertained to the Perimeter Embankment. Residual strength parameters were not applied to its foundation, and the resulting factor of safety of 1.7 required no enhancement according to the FS = 1.3 criterion.

Elsewhere, beach deposition from the extended tailings discharge line had not been successful in preventing water accumulation against the Main Embankment. This increased flows in the same upstream toe drain whose effectiveness had been cited as justification for reducing the width of the Stage 6 core.[42]

5 | Panel Observations

Meanwhile, follow-up related to the DSR continued. MEM requested that KP provide the results of its recommended direct shear testing, which essentially confirmed the Stage 6 design ESA factor of safety.[43, 44] But beyond this was another item in KP's response that marked a milestone in two fundamental respects. For the first and only time during the design process, an undrained strength analysis (USA) was performed. This was also the only instance that the foundation clay behaviour would be taken as other than that of stiff and highly overconsolidated material. Using a typical S_u/σ_V', of 0.25 for soft, normally consolidated clays, KP found a USA factor of safety of 1.1 for the Stage 6 configuration. Not recognizing that this strength might indeed be the operational strength under static loading conditions, KP concluded that "there is also sufficient undrained strength in the lacustrine unit for the embankment to remain stable." This conclusion would henceforth never be called into question.

Not recognizing that this strength might indeed be the operational strength under static loading conditions, KP concluded that "there is also sufficient undrained strength in the lacustrine unit for the embankment to remain stable." This conclusion would henceforth never be called into question.

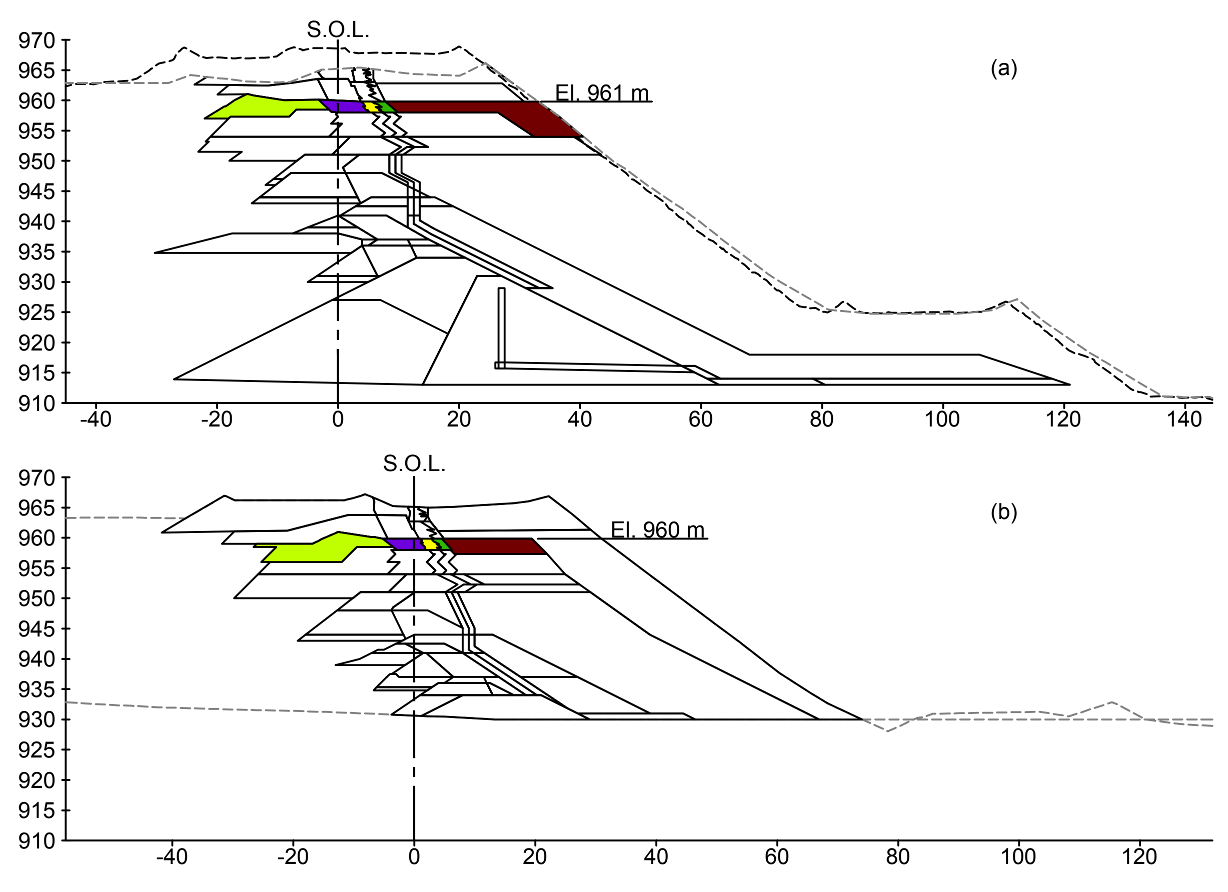
Operation of Stage 6 throughout 2009 and 2010 highlighted other matters. In 2009, movements in the GLU recorded at Inclinometer SI01-02 resulted in expanding the Main Embankment buttress in the immediate area. This proved to be effective in arresting further displacements.[45] By 2010, the buttress had been extended along the west side of the Main Embankment, but still remained to be completed along its entire length.[46] In another development, a tension crack appeared at the downstream edge of Zone C at Sta. 3+400 of the Perimeter Embankment. Although interpreted to be an artifact of near-surface movement, a follow-up stability assessment was nonetheless recommended.

Inadequate tailings beach development along the Main and South Embankments was flagged yet again, this time in an MEM inspection. Noting that an above-water beach was a requirement of the design, the inspector considered its absence at the southeast corner of the Main Embankment to be a "Departure from Approval" and ordered that a beach be "re-established as soon as possible in this area to meet the design objectives."[47]

5 | Panel Observations

5.4.7 STAGE 7: 2011 — 2012

FIGURE 5.4.7: STAGE 7 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

In 2011, the Engineer of Record (EOR) responsibilites were transferred from KP to AMEC, and with them the design of Stage 7 for a height increase of 2.5 m. No new Zone C fill would be added to flatten the downstream slope, and no buttress expansion would be conducted. Continuing the stability analysis protocols from Stage 6 and the 2006 DSR, AMEC found that the ESA factor of safety using residual strength for the foundation GLU was unchanged from the Stage 6 value of 1.4[48] for the Main Embankment. Similar conclusions applied to the factor of safety for the Perimeter Embankment.

The same year also saw the completion of the 2011 Geotechnical Site Investigation, the first major foundation exploration program since Stage 1. It consisted of 11 sonic drillholes, with piezometers installed in each, plus three new inclinometers.[49] Emphasis was on definitively evaluating the DSR hypothesis that the glaciolacustrine foundation soils might contain pre-sheared planes of weakness and the operative residual strengths that would accompany them.

Careful inspection of recovered core revealed no indications of slickenside features and no evidence of pre-shearing. Thus, residual strengths need no longer be considered. Neither, it was concluded, did these conditions indicate that the 2010 crack in the Perimeter Embankment was attributable to weak soil conditions in the area.

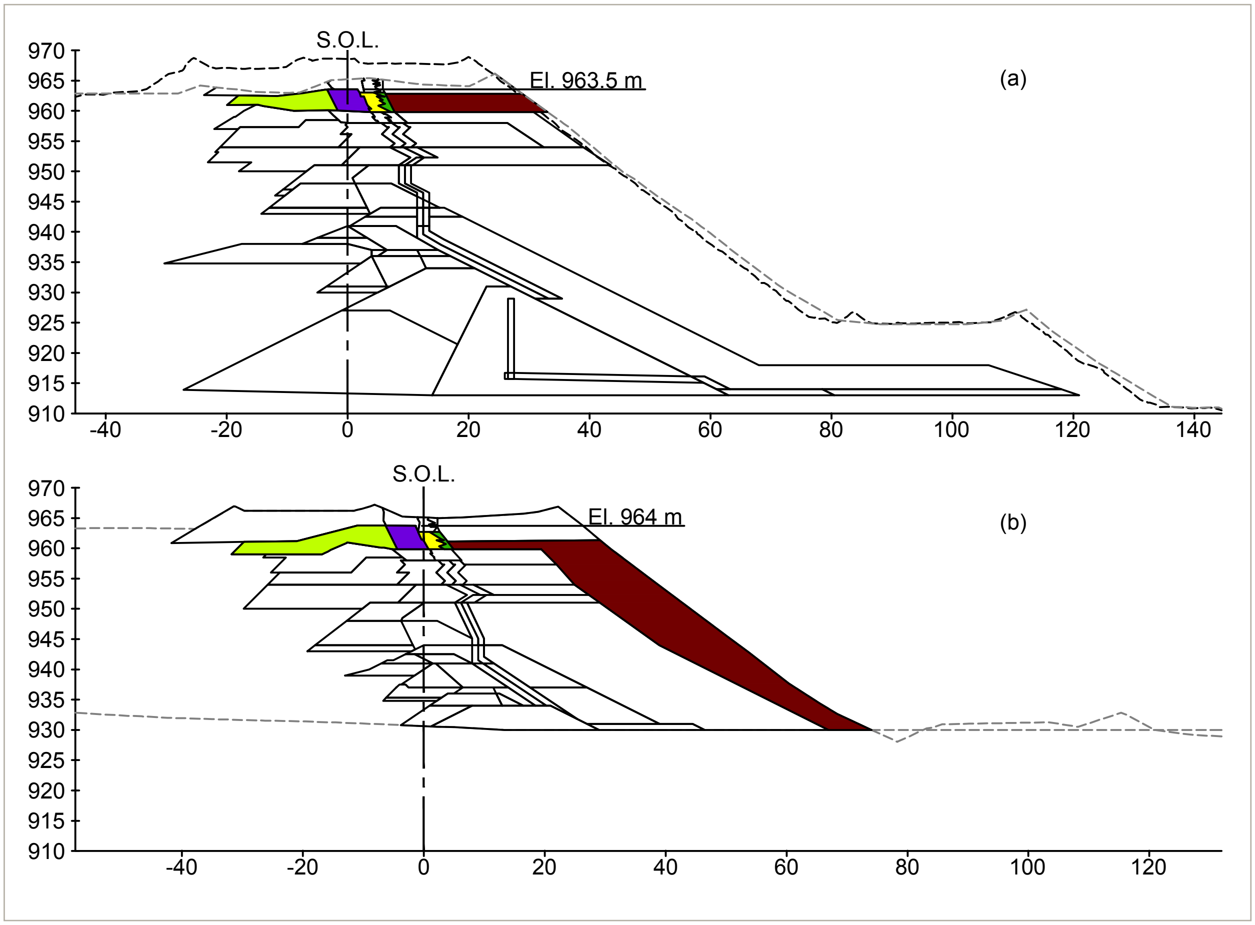
With respect to stress history, the 2011 report further concluded that the GLU was overconsolidated, consistent with previous interpretations. The softer conditions in monitor well GW96-1A adjacent to the Perimeter Embankment that MEM had questioned in 2005 were said to be "not of significant concern in this instance as the drillhole location is approximately 140 m further downstream from the current toe of the dam." In fact, the report said, "based upon available information, foundation conditions along the Perimeter Embankment appear more favourable than those along the Main Embankment" in terms of the presence and extent of clay-rich zones within the GLU.

At the Main Embankment, piezometers were installed generally beneath the buttress where measured pore pressures would be reflective of additional fill. This was not the case at the Perimeter Embankment, where all of the new piezometers were located 15–20 m from the downstream toe. Similarly, Inclinometer SI11-04 installed during the program was 15 m away.

5 | Panel Observations

5.4.8 STAGE 8: 2012 — 2013

FIGURE 5.4.8: STAGE 8 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

Stage 8 was initially designed as a 3.5 m raise, then increased to 5 m with an accelerated construction program. It would change to conventional "centreline" raising from the previous "modified centreline" that had progressively shifted the raises upstream. Stage 8 fill was added only to the crest of Stage 7 Main Embankment,[50, 51] while the Perimeter Embankment was widened as well. But in both cases, flattening of the Stage 5 "interim" oversteepened slope to 2H:1V was deferred yet again—not until completion of Stage 5 raise as first proposed, but this time until completion of the entire dam.

Flattening of the Stage 5 "interim" oversteepened slope to 2H:1V was deferred yet again—not until completion of Stage 5 raise as first proposed, but this time until completion of the entire dam.

In evaluating the stability of the steepened slope, AMEC returned to the peak-strength interpretation for the GLU materials based on the findings of its 2011 field program. For a peak effective-stress friction angle of 28°, the ESA factor of safety was found to be a barely adequate 1.31 [52] for the Main Embankment.

The 2011 investigation showed the GLU materials at Section D of the Perimeter Embankment to be deeper than at the Main Embankment. In stability analyses at Section D near the breach, the critical failure surface did not reach the GLU and remained within the overlying foundation till, producing a much higher factor of safety of 1.77.

The larger issue of what minimum factor of safety should be required was addressed in a September 19, 2012 communication from MEM to MPMC that deserves to be quoted at length:

The factor of safety for the main embankment is only marginally above the short-term design criteria of 1.3... AMEC has interpreted Table 6-2 from the 2007 Dam Safety Guidelines somewhat differently than I have seen in the past. This table recommends a minimum factor of safety of 1.3 at the end of construction and 'before reservoir filling' and a factor of safety of 1.5 at the 'normal reservoir level.' AMEC has interpreted the construction period as the entire pre-closure period, and this is open to debate. However, I consider that sufficient mitigation measures are in place (i.e., piezometer trigger thresholds) to support this more liberal interpretation in this instance. [53]

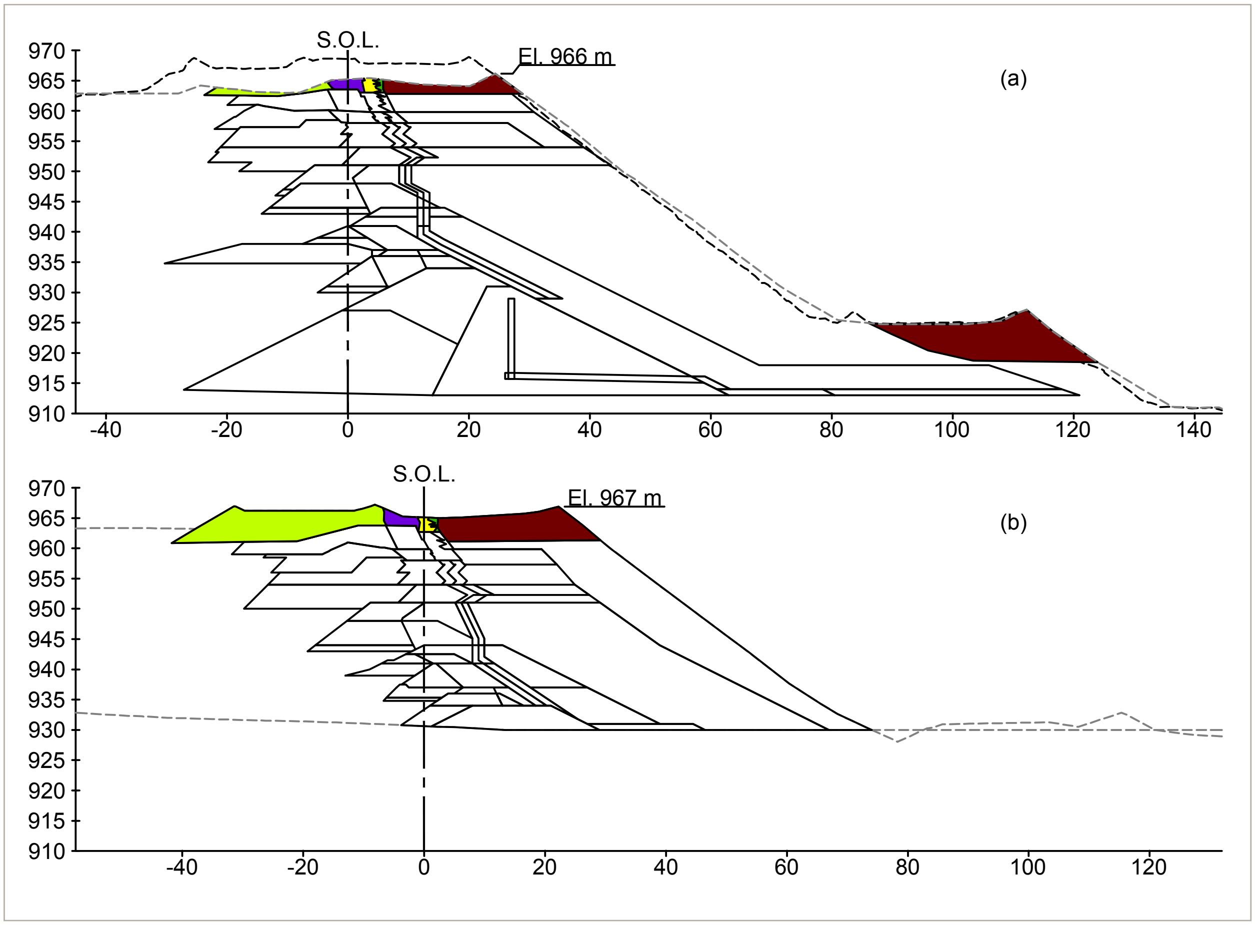
Although questioning AMEC's interpretation of the Dam Safety Guidelines, MEM was prepared to accept FS = 1.3, but only in conjunction with the Observational Method.

In other matters, the recurring problem of tailings beach development was not directly addressed in the 2012 inspection report, but an airphoto showed no tailings beach over approximately 40% of the impoundment perimeter.[54] The report also noted that seepage had been present at the toe of the Perimeter Embankment near the breach section and that it had moved from previous years. Based on interviews with MPMC personnel, the Panel believes that the likely source of the apparent seepage was actually a buried outlet of the upstream toe drain.[55, 56]

5 | Panel Observations

5.4.9 STAGE 9: 2013 — 2014

FIGURE 5.4.9: STAGE 9 (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT



5 | Panel Observations

Stage 9, whose construction was being completed when the breach occurred, encompassed a period of intense activity with a number of seminal events in the months, weeks and days preceding the failure. While AMEC remained the EOR until the planned completion of Stage 9 to El. 970, BGC would officially become the EOR beginning with construction of the planned Raise 10. Consequently, 2013 to 2014 was also a period of transition, with overlap in activities, if not responsibilities.

AMEC's April 11, 2013 design for Stage 9 planned a substantial 6.5 m height increase by adding fill to the crest of Stage 8. Retaining the peak-strength interpretation for the GLU foundation materials, AMEC found that raising the Main Embankment buttress to El. 925 m would be needed to nominally achieve a minimum ESA factor of safety of 1.3.[57]

Commenting on the implications of this value, MEM's remarks on July 29, 2013, echoed its previous concerns:

The stability analyses indicate that the FOS for the 'Main Embankment' only marginally achieves the short term CDA design criteria of 1.3. ... Previous correspondence from MEM has highlighted the difference in interpretation of the CDA Guidelines. AMEC has considered the construction period to be the entire 'pre-closure' period while CDA Guidelines, Table 6-2 recommends a minimum FOS of 1.3 'before reservoir filling,' and a FOS of 1.5 at the 'normal reservoir level.'

MEM requires a commitment from Mount Polley that they are moving toward increasing these FOS for the main embankment as part of subsequent dam raises in an effort to move toward achieving a long term FOS equal to 1.5. It is expected that Mount Polley will continue their transition to centerline construction and provide additional buttressing with time.[58]

This marked a major change in direction. A factor of safety of 1.5, not 1.3, would become the governing criterion. Moreover, buttressing could no longer be deferred for either embankment. A factor of safety of 1.58 had been calculated for Section D of the Perimeter Embankment, once more unaffected by the GLU foundation materials. But even this value was approaching the new minimum of 1.5 that MEM was now aiming to enforce, and buttress preparation needed to begin.

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By the end of the 2013 construction season, pre-stripping for a buttress around the Perimeter Embankment had been completed, including the area of the breach section.[59] In a Panel interview, the contractor who performed the work stated that portions of this area remained open at the time of the breach,[60] an assessment confirmed by MPMC.[61, 62]

5 | Panel Observations

Meanwhile, attention was turning to longer-term prospects for continued dam raising, and the outlook was not good. BGC made explicit the connection between the structural limitations of the dam and the ever-growing volumes of surplus water it was being called upon to contain. In a June 18, 2013 memorandum, it stated:

A continuous beach along the complete upstream length of the dam is the design requirement necessary for dam stability and needs to be achieved moving forward regardless of the final targeted crest elevation. The current water pond surplus does not allow for the development/maintenance of above-water beaches. [63]

It elaborated on this topic a month later, on July 25, 2013:

An above-water tailings beach separating the till core from the reclaim water pond constitutes a fundamental design element of the dam. Without a wide above-water beach, the MPMC tailings dam is effectively being operated as a water-retaining dam, with the water pond effectively in direct contact with the till core, separated by only a narrow zone of tailings or waste rock. [64]

During the ensuing months, this chronic water-surplus problem would become acute. For years, dam raising had managed to stay one step ahead of the rising water. But on May 24, 2014, the water caught up. With Stage 9 nearing completion, what was described as "seepage flow" was observed over the dam core.[65] Intensive surveillance and construction activity over the following days and weeks succeeded in raising low areas around the embankment perimeter, restoring containment integrity, and saving the dam from overtopping failure.

For years, dam raising had managed to stay one step ahead of the rising water. But on May 24, 2014, the water caught up.

As the gravity of the water problem was becoming apparent, so was the consequent necessity of dam raising beyond Stage 9. MPMC required some estimate of future dam footprint so that prerequisite stripping of additional areas could commence immediately. BGC responded on October 22, 2013, with a memorandum that outlined an approach to dam raising that resurrected the residual-strength interpretation for GLU, while at the same time establishing new factor of safety criteria conforming to MEM's 2013 directive.[66]

This approach was formalized in BGC's design report for Stage 10 issued on July 25, 2014, just eight days before the breach.[67] The proposed raise would achieve a minimum FS = 1.5 for the Main Embankment using peak effective-stress strength for the GLU and full dissipation of load-induced pore pressures. But this new design philosophy would go one step further.

5 | Panel Observations

Notwithstanding AMEC's 2011 subsurface investigation, a "more conservative" approach would be taken by allowing for the possibility of brittle behaviour or pre-shearing in the GLU. This would apply an additional criterion of FS = 1.1 using residual strength in the GLU for what was characterized as a "reasonable worst-case scenario." So the residual-strength interpretation was now reintroduced after first being suggested in the 2006 DSR, adopted in design of Stages 6 and 7, then abandoned in design of Stage 8.

The BGC report also commented on the application of the Observational Method to these conditions. Citing its chief progenitor Ralph Peck, the report recognized that this design strategy requires preplanned actions to deal with "every unfavourable situation that might be disclosed by the observations."[68] But it also acknowledged that any brittle behaviour detected by the instrumentation would result in strength reduction too rapid to recognize and respond to. Hence the need, it said, for the minimum FS = 1.1 and its associated residual strength interpretation as a contingency. As a result, the existing buttress on the Main Embankment would be raised, and a new buttress about 8 m high would be added to the Perimeter Embankment. This was to include what would become the area of the breach.

In a final irony, the Stage 10 buttress was scheduled for construction on the Perimeter Embankment in late 2014 or early 2015. Had it been in place on August 3, 2014, the dam would have survived.

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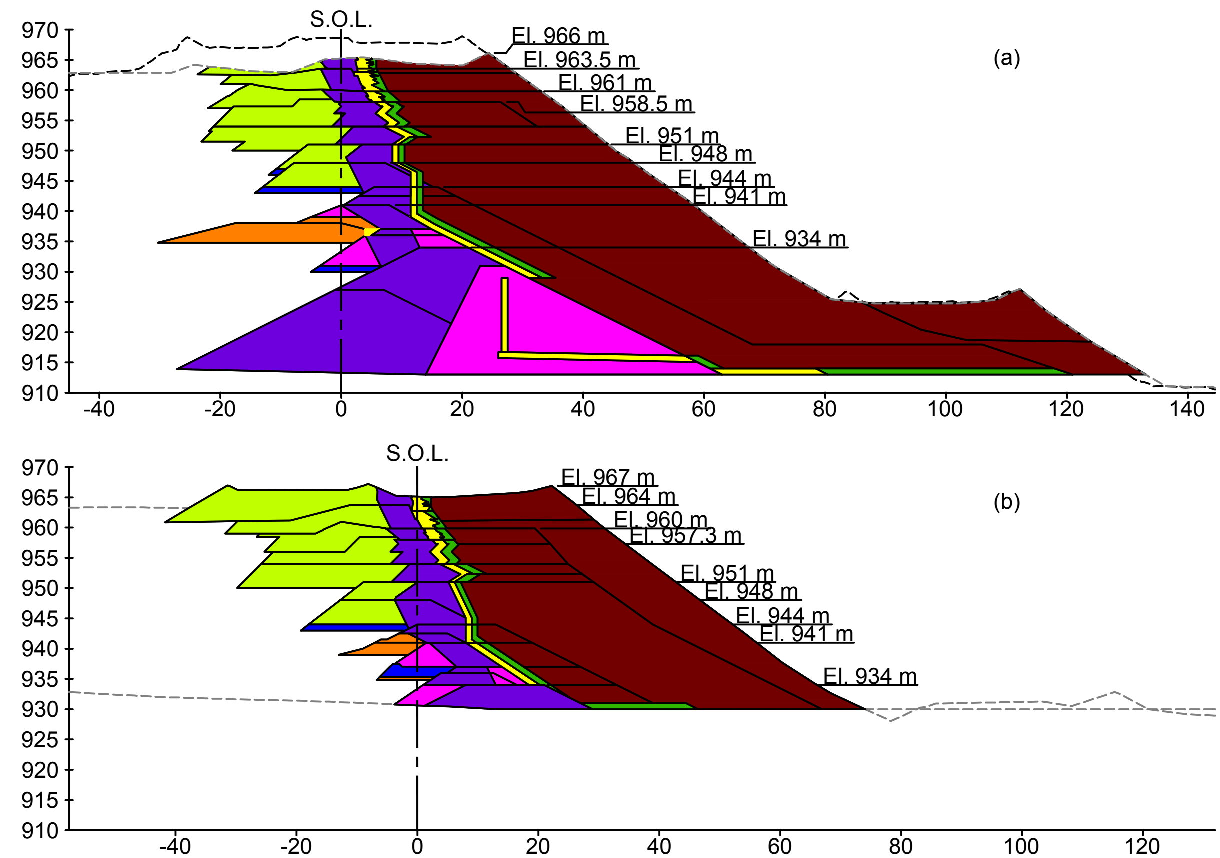
5 | Panel Observations

FIGURE 5.4.10: DAM CONFIGURATION ON AUGUST 3, 2014. (a) MAIN EMBANKMENT (b) PERIMETER EMBANKMENT AT BREACH SECTION



5.4.10 COMMENTARY

The preceding account is in many ways a story of too little, too late. From the beginning, dam raising proceeded incrementally, one year at a time, driven by impoundment storage requirements for only the next year ahead. More reactive than anticipatory, there was little in the way of long-term planning or execution. This was most clearly displayed by the absence of an adequate water balance or water treatment strategy, and the overtopping failure that nearly resulted. Moreover, the related absence of a well-developed tailings beach violated the fundamental premise of the design as a tailings dam, not a water-storage dam.

The preceding account is in many ways a story of too little, too late. From the beginning, dam raising proceeded incrementally, one year at a time, driven by impoundment storage requirements for only the next year ahead.

The same problem was apparent in production and scheduling for mine waste used in dam construction. The design was caught between the rising water and the Mine plan, between the imperative of raising the dam and the scarcity of materials for building it. Something had to give, and the result was oversteepened dam slopes, deferred buttressing, and the seemingly ad hoc nature of dam expansion that so often ended up constructing something different from what had originally been designed.

Ultimately, the tortuous, incremental nature of this process, and the constraints under which it was conducted, caused it to lose sight of basic precedent. With a slope steepness ordinarily reserved exclusively for rockfill dams on sound rock foundations, the Perimeter Embankment at the breach section was allowed to reach a height of almost 40 m with an unbuttressed downstream slope of 1.3H:1V.

Not just the design process but also the design itself had shortcomings. Even if not contributing directly to the failure, some design details were problematic. Already thin to begin with, reducing the core width from 8 m to 5 m made it even more vulnerable to differential settlement and cracking. Both the filter and transition zones were just 1 m wide, placing great demands on their performance. Yet in a sampling of as-placed Zone S filter gradations, the Panel found that 30% were too coarse to meet the $D_{15}<0.7$ mm filter criterion and 70% had internally unstable grading,[69, 70] with only about 25% satisfying both filter and internal stability requirements.

5 | Panel Observations

There were ambiguities in the governing factor of safety, adapted from CDA Guidelines never intended for tailings dams. An FS = 1.3 design criterion using peak effective-stress strength left little margin for error, and trigger-level factors of safety for critical piezometric conditions were even lower at 1.1. Such values may have made it easier to rationalize the departure from slope precedent, but harder to gauge just how closely dam raising was approaching the edge of the cliff.

There was an oversimplified conception of the complex stratigraphy of the glacial deposits described in section 5.2. An Upper GLU unit had been encountered in groundwater well GW96-1A and a lower unit in sonic borehole VW11-10. But only the lower unit was included in stability analysis of the Perimeter Embankment, and it had no influence on calculated factors of safety. The possibility that the upper unit might be present beneath the Perimeter Embankment was not accounted for in conceptualization of geologic conditions. More than this, its stress history was much less favourable.

Yet the overarching problem, and the one the Panel finds most troubling, is the failure throughout to adopt the appropriate undrained strength interpretation for the glaciolacustrine silts and clays in the foundation. These materials were assumed everywhere to be stiff, and therefore overconsolidated, although there was never any attempt to quantify their degree of overconsolidation or stress history. And even if they were overconsolidated to begin with, it was not recognized that the increasing loads imposed by the dam as it grew higher would eventually cause them to reach a normally consolidated state.

The overarching problem, and the one the Panel finds most troubling, is the failure throughout to adopt the appropriate undrained strength interpretation for the glaciolacustrine silts and clays in the foundation.

There is a fundamental difference in pore pressure behaviour between these two conditions and the undrained strengths they produce. Overconsolidated clays are dilatant during undrained shearing. That is, they tend to increase in volume, producing no positive pore water pressures. By contrast, normally consolidated clays are contractive and do develop positive pore pressures. This difference in pore pressure response during shearing makes the undrained strength of a normally consolidated clay lower than the same material in an overconsolidated state. But the design did not account for the undrained strength that would pertain if the dam were to fail rapidly—which proved in the end to be the case.

5 | Panel Observations

Rather, the design was based exclusively on ESA in various forms using peak and residual strengths, all of which neglected pore pressures that would develop in normally consolidated GLU during rapid, undrained shearing. The design never incorporated an undrained strength analysis (USA), except in one instance. A USA performed for Stage 6 using an undrained strength typical of normally consolidated clays produced a factor of safety of only 1.1. But this was not seen to be the operative strength and was not considered further here or in subsequent stages. If undrained strength behaviour had been properly understood and applied throughout, the outcome could have been much different.

The Observational Method was invoked early on as the basis for design. This commonly accepted approach uses observed performance from instrumentation data for implementing preplanned design features or actions in response.

But there were a number of problems in applying this strategy to the Mount Polley dam that are treated in the following section. The first was simple geometry. The Observational Method relies on measuring the right things in the right places. While this was comparatively easy over the 1,000 m length of the Stage 1 dam, it became increasingly difficult as the length grew to 5 kilometres (km) by Stage 9. Nor could foundation instrumentation be installed beneath the dam crest and slopes where piezometric data mattered most. The slopes were too steep to be accessible, and few instruments installed on the crest could survive the near-constant construction there for very long. As a result, the few piezometers and inclinometers at the Perimeter Embankment were too far beyond the dam toe to produce critical data, and too far between to cover the area where the breach occurred.

Even more fundamentally, the piezometers as installed were only capable of measuring static ("water table") pore pressures and, if properly located, those induced by applied loads. But piezometers cannot measure pore pressures induced by undrained shearing because the location of the failure surface on which to measure them cannot be known in advance.

The remaining problem is that the Observational Method is useless without a way to respond to the observations. Constructing buttresses and obtaining the necessary mine waste had been hard enough under ordinary circumstances. Were the instruments to warn somehow of a rapidly developing failure, there would be no way to respond in time to avert it. Hence, the Observational Method could not be relied on to determine the need for buttressing, so the buttress would be required regardless.

This fact was belatedly recognized in the Stage 10 design just days before the breach—the final fateful instance of too little, too late.

5.5 INSTRUMENTATION AND MONITORING

5.5.1 PRE-BREACH MONITORING OF TSF

Geotechnical instrumentation was installed beginning with Stage 1 of Main Embankment construction in 1996 and early 1997. During the initial phase, the focus was on vibrating wire piezometers, survey monuments, drain flow monitoring, and monitoring wells.[71] The first inclinometers on the Main Embankment were installed in July 2001. During the pre-breach period, instrumentation was installed at a total of 12 sections for the three embankments, Main, Perimeter and South (see Appendix F, Drawing F1). Further details of the inclinometers, piezometers, and drain flow monitoring during pre-breach monitoring are presented in Appendix F, Attachment 1.

A total of 10 inclinometers were installed after the start of operations. Of these, nine were still operating when the failure occurred: six at the toe of the Main Embankment and three along the toe of the Perimeter Embankment. One of the inclinometers along the Perimeter Embankment (SI11-04) was still being read, but was not reliable due to "a compression failure"[72] and had been replaced by Inclinometer SI12-04. Therefore, the Perimeter Embankment had two reliable inclinometers.

Vibrating wire piezometers were installed during ongoing construction activities at the 11 sections shown in Drawing F1. The last two sections (J and K) were added in 2011. As of August 2014, there were a total of 64 operating piezometers and 52 non-operating piezometers, of which 47 in the Main Embankment operated and 34 did not (see Appendix F, Attachment 1). Piezometers can fail not only due to instrumentation defects but also due to construction damage to piezometer cables. For example, during Stage 4 construction from May 2005 to October 2006, "22 piezometers were accidentally destroyed," of which five were repaired.[73] In contrast, a number of the piezometers installed in 1996 and 1998 were still operating in 2014.

Piezometers were installed in the dam foundation, in various embankment components, such as the upstream fill, core, and downstream transition zone, in drains located in the embankment and foundation, and in the tailings upstream from the embankment.

5 | Panel Observations

The majority of the piezometers maintained steady pore pressures during 2014. Typical observations of piezometer pore pressure readings during construction were:

- Pore pressures in foundation piezometers typically increased due to fill placement and dissipated readily following construction.
- Pore pressures in piezometers located in embankment components (core and other downstream layers) and drains were stable.
- Pore pressures in tailings and upstream fill increased in response to the rising pool level.
- Piezometers located near the upstream toe drains experienced less pore pressure increases than those near the pond elevation.[74]

During the first phase of construction in 1996–1997, artesian pressures were observed in three of the six foundation piezometers in the Main Embankment. This prompted the development of trigger levels, or action levels, for many of the piezometers in the foundation and drains.[75]

As part of their annual construction manual in 2012, AMEC developed the instrumentation trigger framework shown in **Table F.1.1**,[76] Appendix F. This framework is for all the inclinometers and the Main Embankment foundation piezometers. The AMEC construction manual states that "embankment construction will be suspended if the inclinometers or piezometers fall under the yellow or red condition described in the Table, and/or if embankment foundation piezometer data indicates a significant increasing trend." No corresponding trigger levels were established for the Perimeter Embankment piezometers because "factor of safety values...are sufficiently high that monitoring of piezometric trends, without defined trigger levels, is deemed sufficient ."[77]

Drain flow of the foundation drains and chimney drain was measured for the Main Embankment during the first phase of construction. Flow measurements were also initiated when similar drains were installed in the Perimeter and South Embankments. Upstream drains were installed in the tailings (also referred to as "upstream toe drains"[78]) at all the dams as they progressed in height, and these flows were also measured starting in 1996. Flows from these drains report to the seepage collection ponds constructed downstream of each dam. These flows were measured monthly (weather permitting) in a manifold for the Main Embankment and across ditch profiles close to the ends of the outlet pipe for the Perimeter and South Embankments.[79] In Appendix F, drain flow readings are shown in **Figure F.1.2**, and these results are further discussed.

Survey monuments were used from Stage 1 construction until about 2010 to measure surface movements of the embankments. These were installed after completing the raise construction.

5 | Panel Observations

5.5.2 PRE-BREACH MONITORING IN BREACH AREA

Locations of the inclinometers and piezometers in the breach area are shown in Appendix F, Drawing F2. In this area, one reliable inclinometer was located about 300 m east of the breach. It was about 15 m to 44 m from the toe of the embankment at the time of the failure. There were nine operating and 13 non-operating piezometers along this section of the Perimeter Embankment. Locations of all the piezometers are shown in the sections in Appendix F, Drawings F3 and F4.

The upstream toe drain in the tailings shown in Drawings F3 and F4 was located at El. 946.3 m. Seepage collection elements for the upstream toe drain are shown in Drawing F4. Flows were conveyed along a drainage ditch to the Perimeter Embankment seepage collection pond at the time of the breach.

5.5.3 PANEL KEY OBSERVATIONS

Section 5.2 clearly demonstrates that foundation conditions in the area of the breach were complex and that the Upper GLU layer was not continuous along the full length of the Perimeter Embankment. The foundation conditions assumed for the initial and ongoing design were based on only four drillholes deeper than 8 m, none directly in the area of the breach. A sentinel control section was therefore not identified, and instrumentation could not be installed to monitor this sentinel section.

Foundation piezometers could not be installed after the downstream slope was constructed at an angle of repose slope (1.3H:1V). Access to the slope was impossible, and piezometers installed from the crest into the foundation would not have been at the correct locations to measure increased pore pressure below the advancing downstream slope. Piezometers downstream from the dam toe (as at Section D) were too far away from the slope to provide any useful information, as was also the case for the inclinometer.

Foundation piezometers could not be installed after the downstream slope was constructed at an angle of repose slope (1.3H:1V).

The complex configuration of the internal embankment zoning made it very difficult, if not impossible, to install replacement piezometers in a specific fill zone at a specific depth.

The complex configuration of the internal embankment zoning made it very difficult, if not impossible, to install replacement piezometers in a specific fill zone at a specific depth. Most piezometers were installed during the construction phases, and many were damaged during those stages.

5 | Panel Observations

While some piezometers provided very useful information (e.g., the tailings piezometers provided pore pressure values that could be applied to slope stability analyses), the Perimeter Embankment instrumentation overall could not have provided any warning of the looming failure. Nor did it provide any monitoring relevant to the critical failure mode.

It should be noted that if failure were to occur suddenly, deformation monitoring could not provide timely warning and a more defensive design would be appropriate. The failure mode encountered here was sudden without any surface evidence and is an example of this behaviour. In their design for the proposed Stage 10, BGC anticipated this issue and recognized that a berm would be required for the Perimeter Embankment. [80]

5 | Panel Observations

5.6 WATER BALANCE

5.6.1 INTRODUCTION

A clear distinction can be made between the water balance actions and outcomes during the Phase 1 Active Mining, the Care and Maintenance period and the Phase 2 Active Mining. **Table 5.6.1** provides a summary of the mining activities, the Mine areas and the water management operating conditions. Appendix G describes in more detail the design objectives, water balance models and their implementation as well as observations found in the TSF Annual Inspection Reports. The consequences of the operational conditions are presented in this section.

TABLE 5.6.1: MOUNT POLLEY MINE LIFE

YEAR	ACTIVITY	MINE PITS	WATER MANAGEMENT OPERATING CONDITIONS
1997 – 2001	Phase 1 Active Mining	Cariboo and Bell	Deficit
2001 – 2005	Care and Maintenance		Neutral
2005 – 2014	Phase 2 Active Mining	Wight, Springer, Southeast Zone, Pond Zone	Surplus

5.6.2 PHASE 1 ACTIVE MINING

From 1997 to 2001 MPMC mined the Cariboo and Bell pits. The area of disturbance in the mining area was quite small and the overall TSF water balance was in a deficit. Water from Polley Lake and surface runoff on-site helped to provide the annual operating requirements.

5.6.3 CARE AND MAINTENANCE

As a result of low copper prices, the Mine suspended operations from October 2001 to February 2005. A small staff was maintained at the Mine and they managed the TSF water balance carefully, making sure that sufficient freeboard was maintained. Towards the end of the Care and Maintenance period, mine development in preparation for start-up was underway and surface water accumulated in the TSF. It was recognized at this time that plans would have to be developed to discharge water to the environment.

5.6.4 PHASE 2 ACTIVE MINING

During the second phase of Active Mining, the footprint of the Mine was expanded to a total of four additional pits and associated infrastructure and waste rock piles. MPMC and the designers knew that there was a surplus of water in the TSF and that strategies had to be developed to discharge water. MPMC also understood the need for permitted discharge from the TSF.

In 2009 MPMC prepared a report entitled *Mount Polley Mine Technical Assessment Report for a Proposed Discharge of Mine Effluent.*[81] In this report, alternative discharge approaches were evaluated. The approach selected was to apply for a permit to discharge water to Hazeltine Creek. A permit amendment was granted on November 7, 2012 that allowed the discharge of up to 1.4 million cubic metres (m^3) per year of filtered water to Hazeltine Creek. The maximum discharge is 35% of flow in the Creek and the window is April to October. In April of 2014 it was estimated that only 170,500 m^3 total discharge was possible, due to constraints of permit requirements.

Discharging small amounts of extra water to Hazeltine Creek did not have a significant impact on the water surplus. Permitting of a water treatment plant was pursued in late 2013 and the Terms of Reference for Discharge was issued by the Ministry of Environment on March 26, 2014. Completion of treatment plant construction was expected in September 2014 or later. This plant would allow total annual discharge of 3 million m^3.

5 | Panel Observations

5.6.5 WATER BALANCE AND TSF CONSTRUCTION

During the life of the Mine, two water balance models were used. The first was compiled by KP and was used from start-up until about 2005. The second was based on a model modified by MPMC to account for the expanded footprint of Phase 2 Active Mining. MPMC updated the water balance regularly with site-specific climatic and operating data as well as bathymetric surveys of the TSF pool. The EOR reviewed the water balances throughout operations except from 2010 to 2014. The Panel could not find any documentation explaining the reason for this change in procedures.

The embankment of the TSF was raised on a regular basis, typically on an annual basis. The design engineers used the outcome of the water balance calculations by MPMC to select the height of the increase. The overall approach was well summarized by KP in 2005 in their report entitled *Design of the Tailings Storage Facility to Ultimate Elevation*: [82]

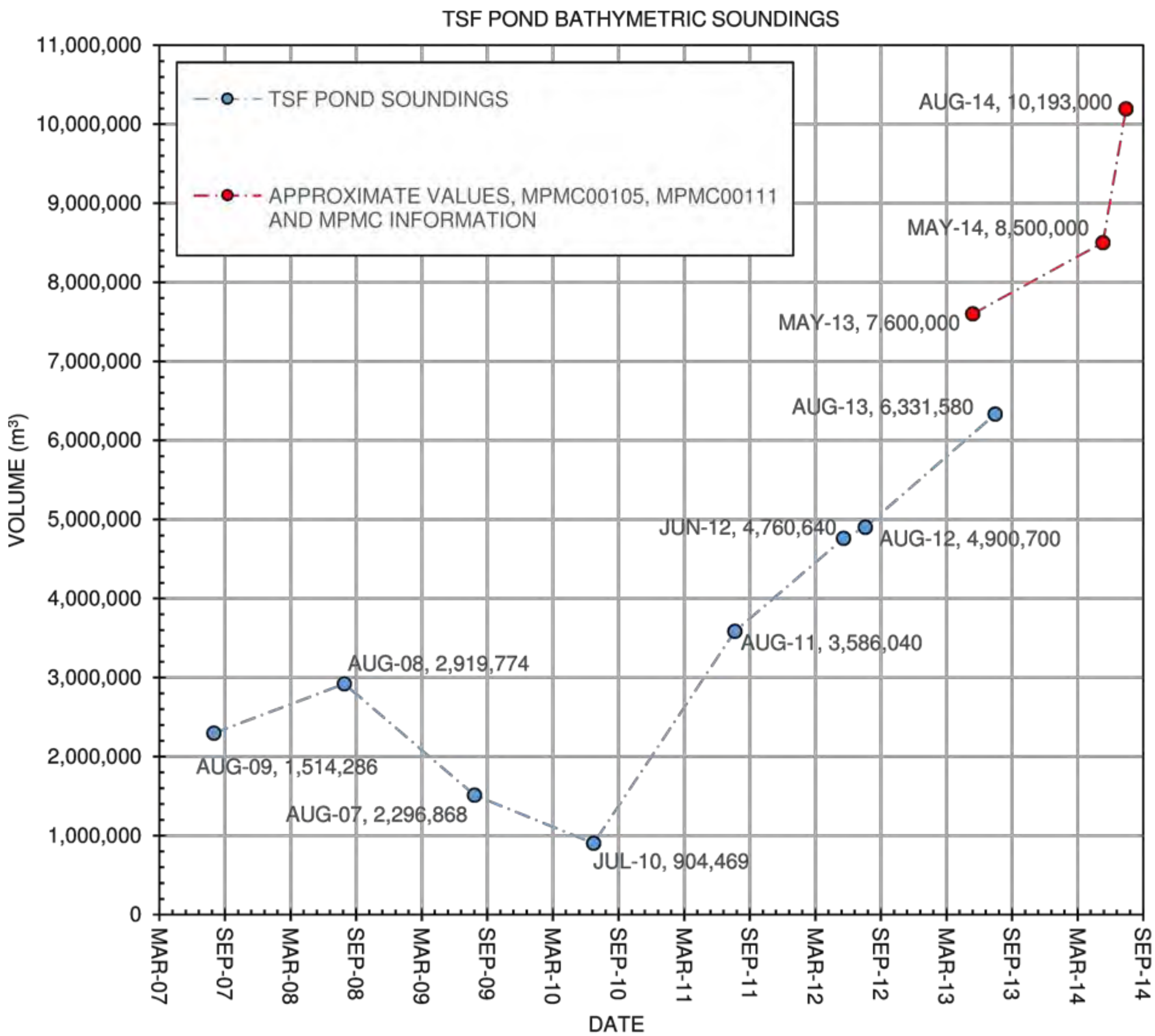
Each embankment raise will provide incremental storage capacity for approximately one-year of production. The filling schedule incorporates sufficient live storage capacity for containment of runoff from the 24-hour PMP volume of 679,000 m^3 at all times, which would result in an incremental raise in the tailings pond level of about 0.39 m, with an additional allowance of 1 m for freeboard for wave run-up.

The water balance model included the site-specific information to the date of analysis, and future conditions were based on average climatic conditions. They did not account for specific wet year conditions.

Figure 5.6.1 shows the accumulation of water in the TSF as determined from bathymetric surveys. The figure also shows approximate volumes reported in the records for three dates (refer to Appendix G).

5 | Panel Observations

FIGURE 5.6.1: WATER ACCUMULATION IN TSF



5.6.6 OVERTOPPING IN MAY 2014

On Saturday May 24, 2014, a potential "dam breach" event occurred at the TSF as a result of a large rainfall, approximately 24 mm in 24 hours, followed by ongoing rain. On Monday May 26 the water level was at El. 966.3 m, which resulted in a freeboard of 0.7 m to the top of the constructed core at El. 967.0 m, as stated in the 2013 Annual Construction Report (refer to Appendix G). The core was found to have a few low spots at 966.3 m (Corner 3), 966.4 m (Corner 2), 965.5 m (Corner 5) and 966.2 m (at the pipe crossing on the Perimeter Embankment). Wet spots and standing water were observed at Corner 3 and the pipe crossing, but no major erosion due to large flows or direct seepage. All the low areas were addressed through emergency construction measures by Thursday, May 29 when the pool water level increased to El. 966.45 m. The top of the Perimeter Embankment was increased to El. 967.3 m. All water collection systems were diverted from the TSF and water was routed for storage in the Cariboo Pit.

The pond elevation was monitored on a daily basis from the end of May until the time of the breach. During that time, construction proceeded to increase the embankment height. On August 3, 2014, the day before the breach, the freeboard was 2.3 m.

5.6.7 COMMENTARY

The way in which the water balance was utilized with annual raises had significant limitations.

The way in which the water balance was utilized with annual raises had significant limitations. Construction of annual embankment raises was based on water balance evaluations using average climatic conditions at the site. This does not provide a reliable approach to establishing adequate capacity for tailings and water storage. Uncertainties in the water balance input parameters combined with uncertainties in climatic conditions and construction schedules cannot provide a robust design for water containment. Construction delays due to site climate or availability of construction materials could impact the targeted capacity. Overtopping of the embankment occurred at selected locations in May 2014.

As indicated in section 4, the Perimeter Embankment did not fail due to overtopping; however, storing large volumes of water in the TSF had other implications.

5 | Panel Observations

Throughout most of its term as the EOR, KP emphasized the importance of maintaining a beach width of at least 10 m. The Panel does not consider this to be a beach. Nevertheless, the principle was clear: the Mount Polley TSF embankments were not designed as water-retaining dams, and a beach would provide some stabilizing function. It was impossible to maintain beaches against all the embankments throughout the year during the last years of operation because of the large volumes of water stored in the TSF. Section 5.4 summarizes the chronic problems experienced in beach development.

MPMC was aware of the water surplus conditions at the start of Phase 2 operations. The pond volumes in **Figure 5.6.1** show that the last number of embankment raises were necessary to store water and not necessarily much higher tailings production. It is not clear to the Panel why it took so long to design and implement a water treatment strategy that would provide for a significant reduction in the amount of surplus water stored on the TSF.

It is not clear to the Panel why it took so long to design and implement a water treatment strategy that would provide for a significant reduction in the amount of surplus water stored on the TSF.

The pore pressure in the tailings piezometer at the breach location increased as a result of the higher pool elevation (refer to section 5.5). This happened despite the presence of the upstream toe drain. The higher pore pressure had a secondary effect on the overall slope stability.

Finally, the volume of water in the pool at failure, about 10 million m^3, resulted in a much larger loss of solids from the TSF due to erosion than might have occurred if there was a smaller pool (refer to Appendix C). And a wider beach of unsaturated tailings might have delayed breach development long enough for emergency actions to have been taken.

5 | Panel Observations

ENDNOTES

1) Klohn Crippen Berger, 2014, Site Investigation Progress Report No. 1, Report to BC Ministry of Energy and Mines.
2) Kulhawy, F.H. and Mayne, P.W., 1990, "Manual on Estimating Soil Properties for Foundation Design", Electric Power Research Institute (EPRI), EL-6800, 308 p.
3) MP10012
4) MP00054
5) MP10012
6) U.S. Dept. of the Navy, 1982, Soil Mechanics Design Manual 7.1, NAVFAC DM-7.1, 205 p.
7) MP00001
8) MP00005
9) MP00001
10) MP00054
11) MP00083
12) MP00069
13) MP00019
14) MP10009
15) MP00008
16) MP00012
17) MP00008
18) MP10032
19) Panel Interview, 12/12/14.
20) SUB00023
21) MP00011
22) MP00013
23) MP00014
24) MP00021
25) MP00118
26) MP00038
27) MP00021
28) MP00126
29) MP00026
30) MP00031
31) MP00076
32) MP00137
33) MP00139
34) Panel Interview, 12/12/14.
35) MP00028
36) MP00033
37) MP00077
38) MP00104
39) MP10035
40) MP00032
41) MP00036
42) MP00035
43) MP00222
44) MP00225
45) MP10034
46) MP00037
47) MP00181
48) MP00039
49) MP10012
50) MP00040
51) MP00217

5 | Panel Observations

52) MP00042
53) MP00224
54) MP00043
55) Panel Interview, 10/22/14.
56) MPMC00048
57) MP00045
58) MP000187
59) MP00044
60) Panel Interview, 10/22/14.
61) Panel Interview, 10/22/14.
62) MPMC00048
63) BGC00002
64) BGC00003
65) MP00192
66) BGC00004
67) MP00208
68) Peck, R.B., 1969, Advantages and limitations of the observational method in applied soil mechanics. *Geotechnique*, v. 19, no. 2, pp. 171-187.
69) Kenney, T.C. and Lau, D., 1985, Internal stability of granular filters. *Canadian Geotechnical Journal*, v.22, pp. 215-225.
70) Kenney, T.C. and Lau, D., 1986, Internal stability of granular filters: reply. *Canadian Geotechnical Journal*, v.23, pp. 429-423.
71) MP00019, note that the monitoring wells were for water level and quality measurements outside the TSF; these will not be further discussed in this section.
72) AMEC00164
73) MP00031
74) MP00044
75) MP00019
76) MP00040
77) AMEC00132
78) MP00037
79) MP00044
80) BGC 00007
81) MOE00001
82) MP00026

6 | Analysis of Breach Mechanics

6.1 INTRODUCTION

As demonstrated in sections 5.1 and 5.2, the breach of the Mount Polley Tailings Dam (the Dam) arose because of failure in the foundation of the Perimeter Embankment. According to Ministry of Energy and Mines (MEM) requirements, design with respect to overall stability must be compliant with CDA Guidelines. The specific guideline for a dam under construction and before reservoir filling requires a factor of safety (FS) of 1.3 where:

$$FS = \frac{\text{Available Strength}}{\text{Strength Required for Equilibrium}}$$

That is, the design requires a reserve resistance over and above that required to maintain equilibrium, and with this reserve resistance, it is expected that the structure will perform in a safe manner. This criterion has been accepted for tailings dams during construction, with a higher FS required if the dam has a long service life after it has been filled.

Many potential failure modes have to be considered to meet the requirements that FS = 1.3. The CDA Guidelines are not prescriptive with respect to potential failure modes. It is the obligation of the designer, as EOR, to recognize the potential failure modes, to characterize the operational strength of the materials associated with these potential failure modes, to adopt an appropriate method of analysis to calculate the FS, and to ensure that the FS is equal to or greater than 1.3 during the construction of the dam.

The Perimeter Embankment failed during construction, and hence the FS = 1. It moved sufficiently to lose containment of the impounded water and tailings that flowed out and eroded most of the displaced embankment.

In the following analyses, calculations will show that shear strengths determined by the Panel to reflect undrained failure of the Upper GLU beneath the Upper Till of the foundation are consistent with the strength required for limiting equilibrium, i.e., FS = 1.0.

A detailed explanation of the process leading to failure of the Dam will be presented, and comparisons will be made with the assumptions that underpin the design in order to highlight the deficiencies associated with it.

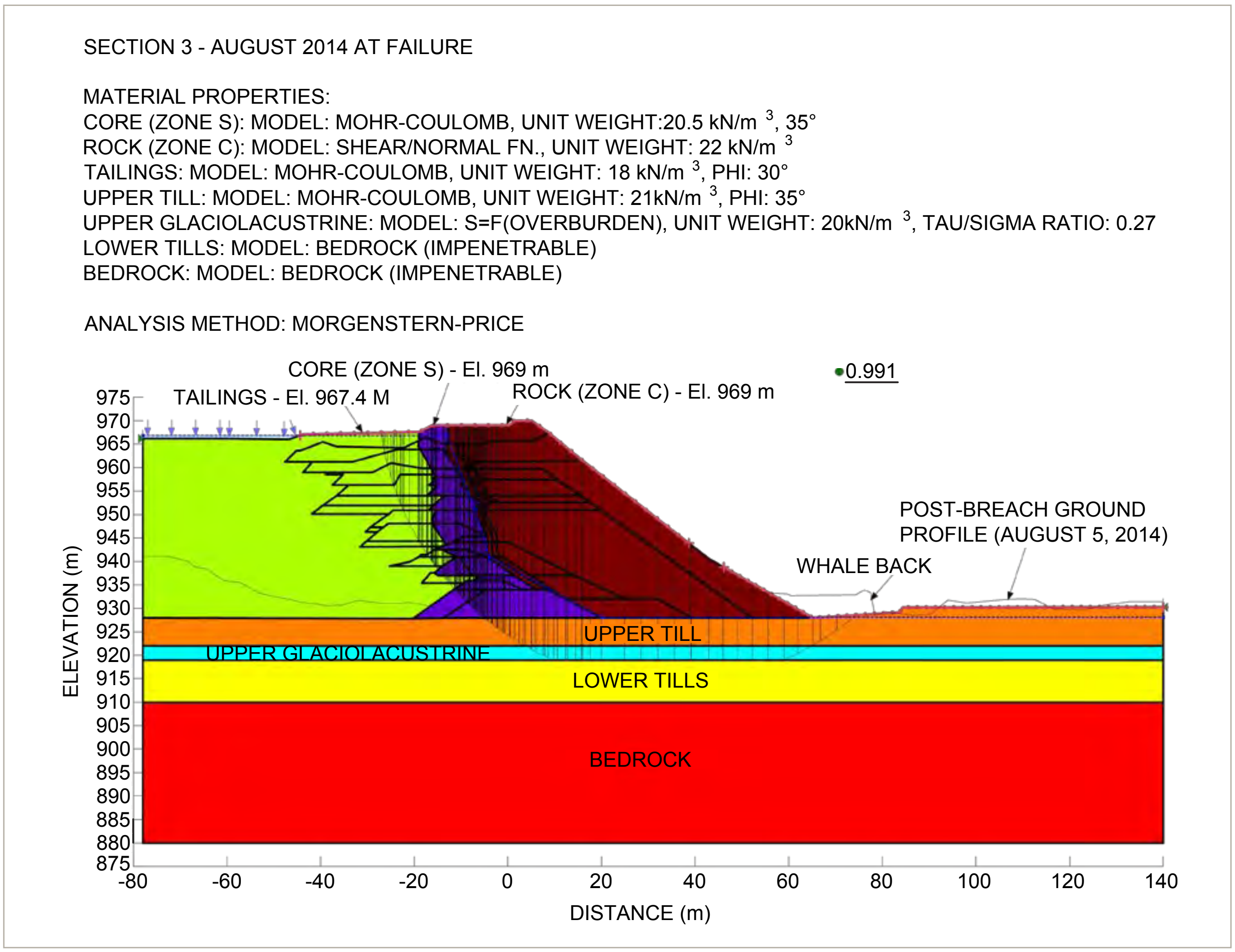
6.2 ANALYSES

6.2.1 LIMIT EQUILIBRIUM ANALYSES (2-D)

Analyses for purposes of designs are conventionally performed on two-dimensional (2-D) sections. Cross-section 3 (see section 5.2; Appendix D) was assumed to represent the stratigraphy more or less in the middle of the displaced mass.

Figure 6.2.1 presents the detailed section. It is based on the last LiDAR survey of the embankment prior to failure, a detailed reconstruction of the top of the structure and pond elevation based on construction inspector reports, and it includes a shallow excavation at the toe of the embankment as reported to the Panel. More details associated with the compilation of this and related sections are presented in Appendix H.

FIGURE 6.2.1: DETAILED SECTION USED FOR LIMIT EQUILIBRIUM ANALYSIS (HIGH WATER TABLE, UNDRAINED STRENGTH RATIO 0.27)



6 | Analysis of Breach Mechanics

The Morgenstern-Price method of stability analysis and the SLOPE-W computer program were used for the computations. Both are recognized standard tools and were also used for the design of the structure at various stages.

Strength properties and densities for each stratum must be defined in order to calculate the FS. The values assumed are also displayed in **Figure 6.2.1**. Only the upper of the two GLUs defined in section 5.2 is included due to its high water content, its lower cone penetration testing (CPT) tip resistance, and overconsolidation ratio (OCR). Except for the strength of the Upper Till unit and the GLU, all strengths and densities are the same as those used in design studies. Based on pressuremeter testing, experience of the Panel members, and the limited pore pressure response during undrained triaxial testing, a frictional resistance of 35° was adopted for the Upper Till. Fully drained conditions are assumed up to failure. The magnitude of the undrained strength ratio in the GLU is then varied until FS=1 is obtained. For the case illustrated in **Figure 6.2.1**, this ratio is 0.27. In this case, the observed level of the pond is carried horizontally through the beach, which would, in most circumstances, be the design basis case (High Water Table case).

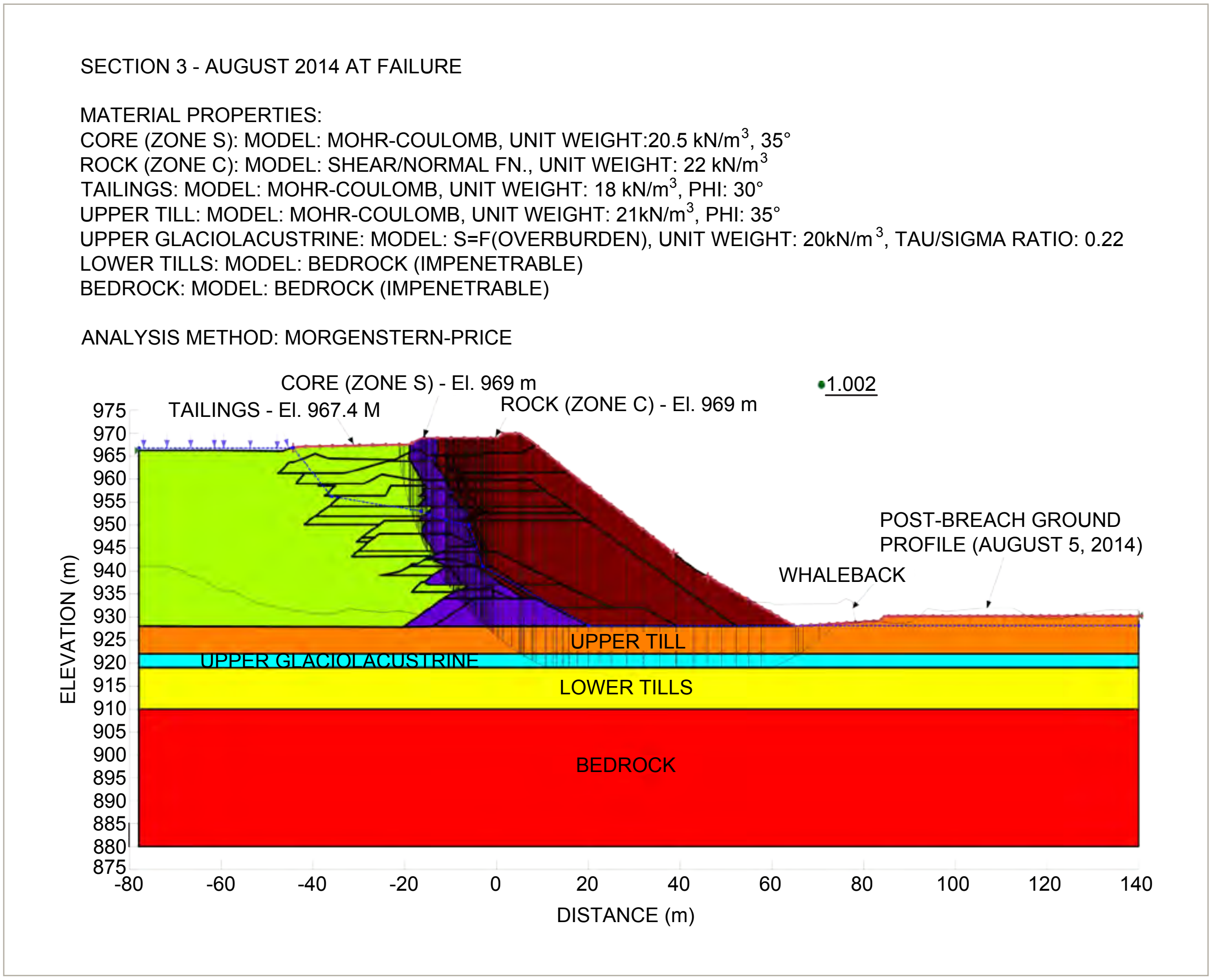
However, the installation of drainage at the upstream face of the core creates downward flow that will reduce the water pressure acting on the core of the Dam. A potential limiting case is shown in **Figure 6.2.2**, and the calculated strength ratio is 0.22 (Low Water Table case). The likely case is between these limits, with the Panel favouring a result above the average, say 0.25.

The calculated value represents the average resistance mobilized by the GLU at the instant of failure. It should be noted that this value lies sensibly in the middle of the range of the measured undrained strength (see **Table 5.3.1**), consistent with the hypothesis that the breach resulted from undrained failure of the GLU at an elevation of about 920 metres (m).

The actual available shear strength will vary with consolidation history as the Upper GLU responds to the stresses imposed by the embankment and the lateral loads transmitted by the impounded tailings and water. This will induce both normal and shear stresses in the Upper GLU. The Panel has not calculated these stresses in any detail. However, it is evident that the maximum applied stresses will substantially exceed the preconsolidation stress level associated with the Upper GLU. This response will reduce towards the breakout zone of the calculated slip surface and beyond, where the influence of applied stresses diminishes. Where the preconsolidation pressure has been overcome, the available shear strength will be that of a normally consolidated soil. Beneath the toe of the embankment and beyond, available strength will be higher, depending upon the local stresses and the preconsolidation stresses. The calculated average resistance reflects this distribution. Appendix E, Attachment 2 shows a comparison between vertical overburden stress and preconsolidation stress.

6 | Analysis of Breach Mechanics

FIGURE 6.2.2: DETAILED SECTION USED FOR LIMIT EQUILIBRIUM ANALYSIS (LOW WATER TABLE, UNDRAINED STRENGTH RATIO 0.22)

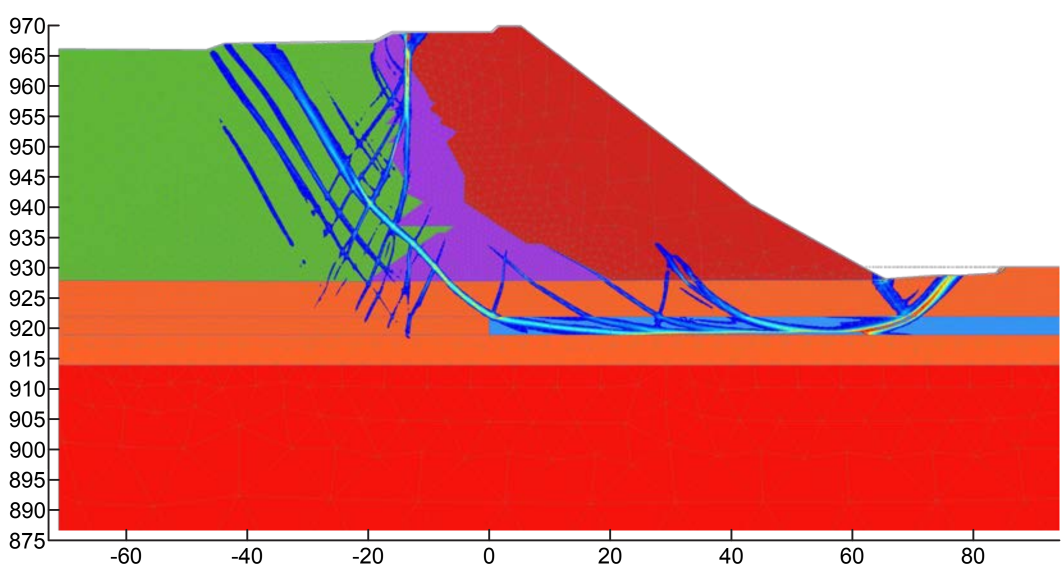


6.2.2 DEFORMATION ANALYSES (2-D)

An alternate way of assessing the undrained failure mechanism is to calculate the deformation patterns that develop at failure. While not a routine design procedure, the means for conducting such analyses are facilitated by powerful numerical simulation tools. In this case, PLAXIS, a well-recognized computer program developed specifically to model soil deformations, was adopted.

Figure 6.2.3 portrays the PLAXIS model at collapse. Prior to creating collapse, the model was constructed with essentially the same input parameters as used in the limit equilibrium analyses, except for the Upper GLU that is given a high strength to avoid yielding. The strength of the Upper GLU is then reduced until a deformation mechanism forms and the embankment collapses. This provides not only a measure of the strength of the Upper GLU at which failure occurs, but also an indication of the deformed shape arising from failure. In the model presented in **Figure 6.2.3**, collapse occurred at an undrained strength ratio of 0.29, which is to be compared with 0.27 calculated from the limit equilibrium analysis that incorporates the same boundary conditions. Lower undrained strength conditions would indicate significantly larger deformations. The figure also indicates the zones of localized strain that develop to facilitate motion. Variations of continuity of the Upper GLU with respect to this case yielded similar results.

FIGURE 6.2.3: PLAXIS MODEL AT COLLAPSE (UNDRAINED STRENGTH RATIO 0.29)



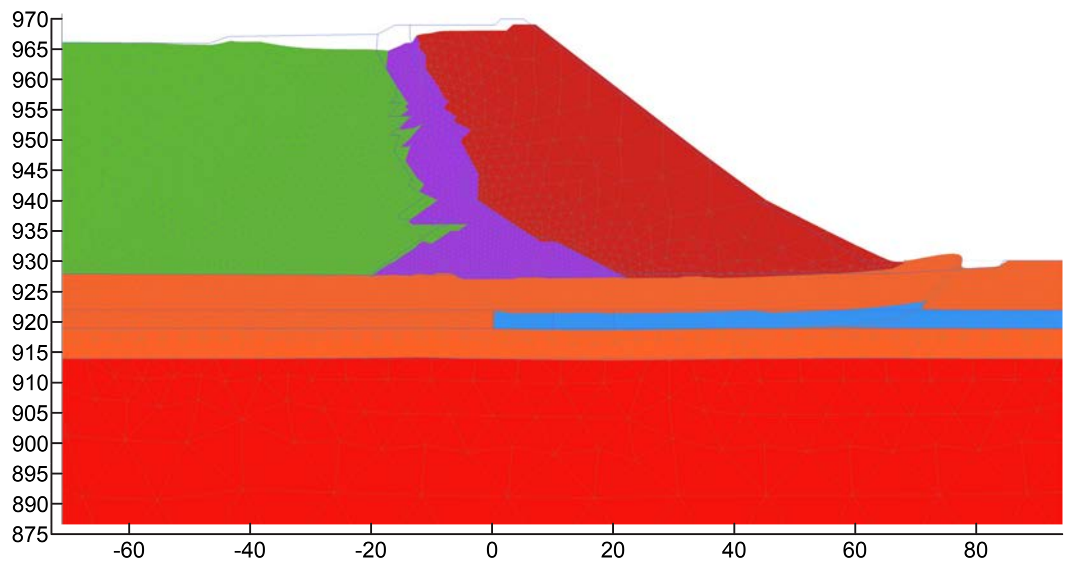
Both the entry and exit of the failure surface in the foundation correspond closely with field observations summarized in **Figure C4.2.2** in Appendix C.

6 | Analysis of Breach Mechanics

Figure 6.2.4 is a scaled-up display to illustrate the calculated deformations. The rotational movement with a lesser lateral displacement are evident. Particularly striking is the thrust feature that occurs very close to the whaleback feature identified in section 5.1. Also significant is subsidence of the crest that allowed overflow to begin, initiating the breach process as described in section 5.1 and Appendix C.

The PLAXIS analyses provide compelling support for the hypothesis that the movements of the Perimeter Embankment arose due to the undrained failure of the Upper GLU.

FIGURE 6.2.4: SCALED-UP FIGURE 6.2.3 TO ILLUSTRATE DEFORMATIONS



6 | Analysis of Breach Mechanics

6.2.3 LIMIT EQUILIBRIUM ANALYSES (3-D)

The length of the breach is relatively short compared to the height of the Perimeter Embankment at failure (~ 40 m). This is expressed as an Aspect Ratio (length/height) and is calculated to be 2.6. At this Aspect Ratio, three-dimensional restraints might be a significant factor influencing the analysis of the breach mechanism. At small Aspect Ratios, the side resistance acting on the potential moving mass increases in significance. This is ignored in the 2-D analyses described above, which are used routinely in design. Nevertheless, the Panel regarded it of value to assess three-dimensional considerations in order to fully explore the factors affecting the breach mechanism.

Three-dimensional limit equilibrium analyses have been conducted using the computer program SVSlope 3D, a widely accepted program for conducting such analyses. The geometry and boundary conditions are a three-dimensional extension of the case illustrated in **Figure 6.2.1**. All soil properties used in the 3-D analysis are the same as those employed in **Figure 6.2.1**.

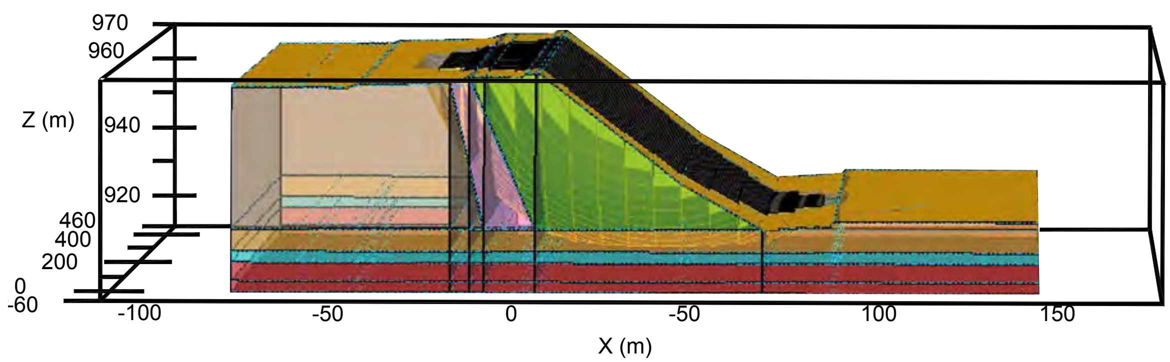
Figure 6.2.5 presents the 3-D case. The FS with an undrained strength ratio of 0.27 and an Aspect Ratio of 2.6 is calculated to be 1.3. This is a significant increase over the 2-D case, and it merits interpretation.

6 | Analysis of Breach Mechanics

FIGURE 6.2.5: 3-D LIMIT EQUILIBRIUM ANALYSIS (UNDRAINED STRENGTH RATIO 0.27, ASPECT RATIO 2.6, FS IS ABOUT 1.3)

CALCULATION METHOD: M-P
SEARCH METHOD: ENTRY AND EXIT
FS: 1.288
CENTRE POINT: X: 37.591 Y: 200.000 Z: 981.233
ELLIPSOID ASPECT RATIO: 2.600, RX:70.168

MODEL



MATERIAL		MATERIAL PROPERTIES	
TAILINGS	MOHR COULOMB	UNIT WEIGHT = 18 (kN/m^3)	PHI=30°
UPPER TILL	MOHR COULOMB	UNIT WEIGHT = 21 (kN/m^3)	PHI=35°
UPP GLU	VERTICAL STRESS RATIO	UNIT WEIGHT = 20 (kN/m^3)	RATIO=0.27
LOWER TILLS	BEDROCK		
ZONE S	MOHR COULOMB	UNIT WEIGHT = 20.5 (kN/m^3)	PHI=35°
ZONE C	SHEAR NORMAL FUNCTION	UNIT WEIGHT = 22 (kN/m^3)	

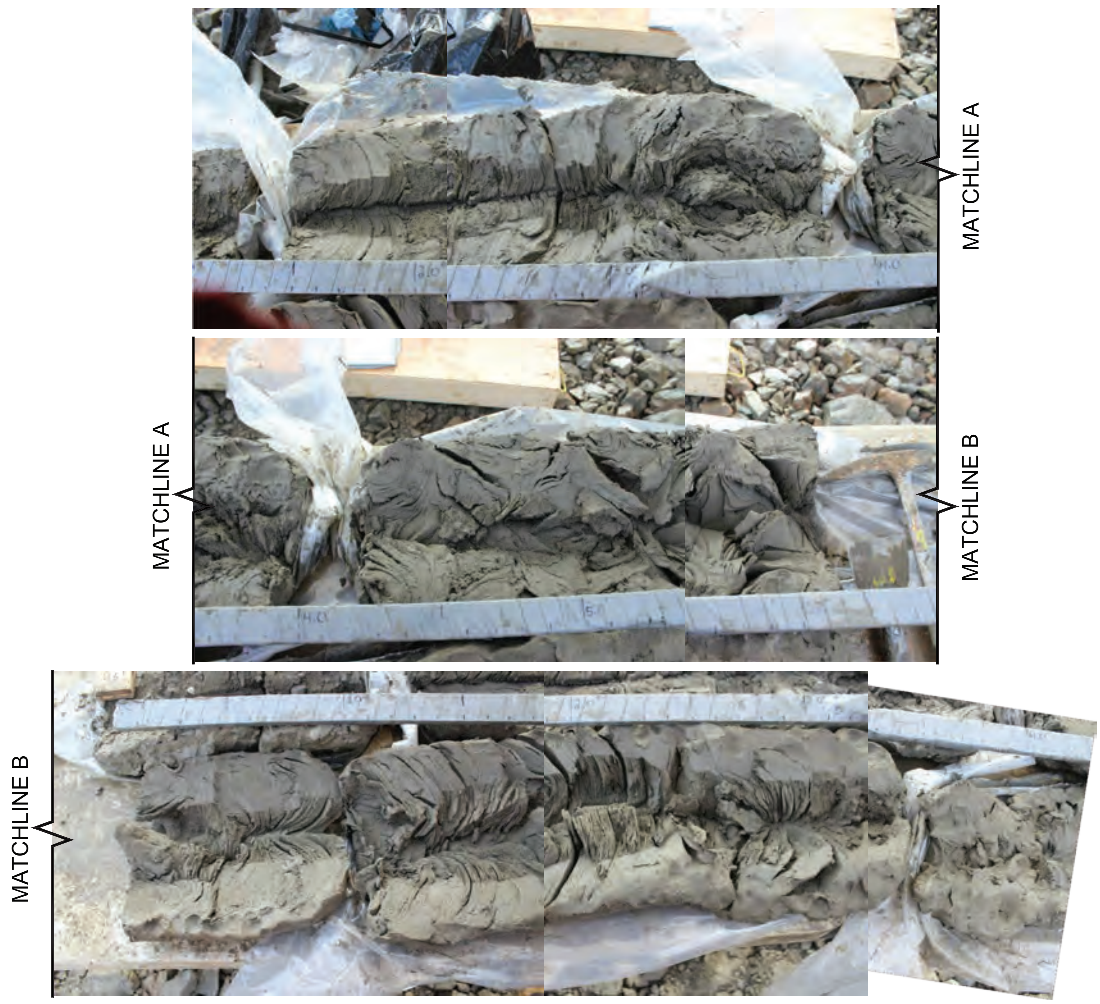
6 | Analysis of Breach Mechanics

As shown in Appendix D, Drawing D19, the sensitivities of the Upper GLU in the failure zone is about 1–3, based on CPT-measured tip resistances. Hence, as deformations developed in the Upper GLU, the available resistance reduced due to strain weakening and soil remoulding. Based on the observed sensitivity, it could have dropped to an undrained strength ratio of perhaps 0.13. Repeating 3-D limit analyses with these values yields an FS of about 1.1, which is close to collapse. Hence, as movements developed, the available resistance of the Upper GLU was reduced due to strain weakening to a degree that the three-dimensional restraints to movements at an Aspect Ratio of 2.6 were overcome. The idealizations involved in these 3-D analyses do not permit greater accuracy than expressed here. Going forward, a review of some of the assumed strength parameters that influenced the 3-D modelling and a more detailed representation of local geology that influence the 3-D results would be warranted. **Figure 6.2.6** displays visual evidence of the remolding processes that have occurred due to shearing of the GLU.

As deformations developed in the Upper GLU, the available resistance reduced due to strain weakening and soil remoulding.

6 | Analysis of Breach Mechanics

FIGURE 6.2.6: TYPICAL SHEARING IN THE UPPER GLU

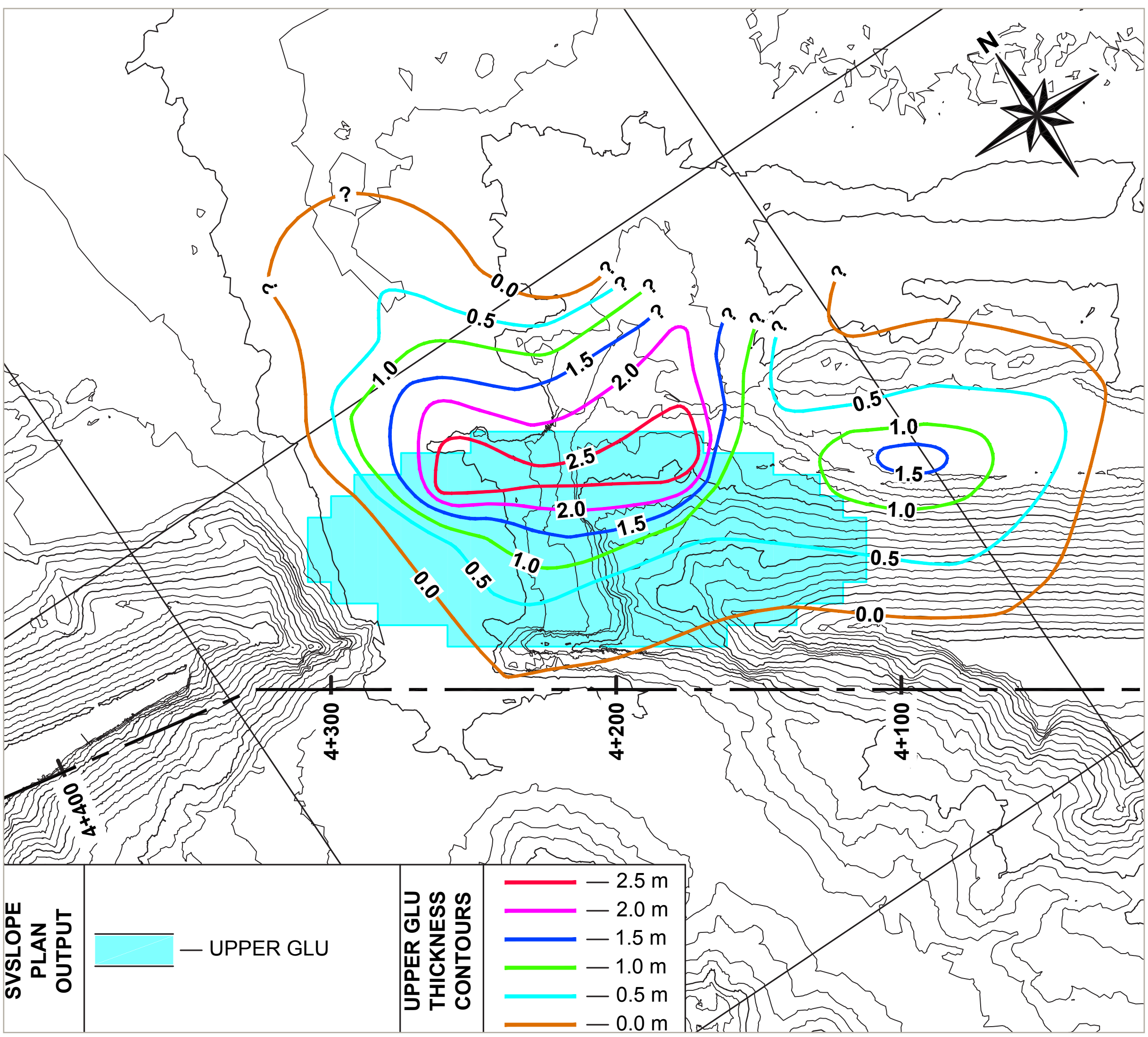


UPPER GLU DEPOSIT, EXHIBITING HEAVILY DEFORMED AND CHAOTIC BEDDING INCLUDING OVERTURNED FOLDS.
NOTE: GREY SCALE BAR UNITS ARE DECIMAL FEET.

6 | Analysis of Breach Mechanics

Additional support for the insight provided by the 3-D interpretation can be found by comparing the footprint of the 3-D analysis with the Aspect Ratio of 2.6 where it intersects the Upper GLU. The distribution of the thickness contours of Upper GLU is presented in **Figure 5.2.6**. This comparison is shown in **Figure 6.2.7**, which indicates a striking fit between the extent of the Upper GLU mobilized in the 3-D analysis (shown in cyan) with the extent of the deepest portion of the Upper GLU.

FIGURE 6.2.7: COMPARISON OF THE 3-D ANALYSIS WITH THE THICKNESS CONTOURS OF THE UPPER GLU



6.3 TRIGGER ANALYSIS

6.3.1 INTRODUCTION

Both the 2-D and 3-D analyses discussed above reflect a simplified interpretation of how failure began and subsequently progressed. They indicate that the foundation was brought to failure under fully drained conditions until the undrained strength was reached and the collapse of the embankment subsequently mobilized the undrained shear strength. After initial failure, the Upper GLU behaved in a strain-weakening manner, reducing its resistance as reflected by the observed sensitivity of the deposit. Ultimately, the increased load associated with the weakening material overcame the residual resistance of the stronger zones, allowing the unconstrained 3-D mechanism to develop. The calculations presented provide average undrained strength ratios at failure that are generally consistent with the magnitudes observed in the laboratory.

In order to understand the failure mechanism in more detail, it is of value to address two questions:

1) **Was the loading path to failure fully drained?**
2) **Was the shear strength at failure mobilized uniformly?**

6.3.2 PORE PRESSURE HISTORY

To address the first question, it is possible to calculate the pore pressure development and dissipation during embankment construction. If the pore pressures remain high, the available shear strength is reduced accordingly. This type of evaluation is an integral part of any stability assessment involving stage construction on soft constructed soils, such as are present beneath the breach zone.

Calculations involve the estimates of stresses on a structure, the magnitude of pore pressure reaction, and its subsequent dissipation with time as construction proceeds through the various stages to completion. The data obtained from consolidation testing (see Appendix E) are used to calculate the rate of pore pressure dissipation. Pore pressures dissipate as a result of water flow to drainage boundaries, and in the case of Upper GLU, dissipation will be enhanced by horizontal flow reflecting the laminated structure of the Upper GLU. Details of the pore pressure predictions for both one-dimensional (vertical only) and two-dimensional (vertical and horizontal) water flow are presented in Appendix H. In the latter case, some estimates of anisotropy of the flow parameters have also been made.

6 | Analysis of Breach Mechanics

The calculated values at the time of failure suggest that an average excess pore pressure of about 50 kPa might exist in the potential shear zone. This is a small percentage of the applied load and, if it does exist, is not particularly consequential. Moreover, in the experience of the Panel, laboratory tests tend to underestimate the coefficients of consolidation in place due to scale effects, and it is likely that the potential for lateral drainage in the analyses due to stratigraphic variations has been underestimated. The Panel concludes that the loading path to failure has been essentially drained with transient episodes of undrained loading. The small peak of pore pressure development beneath the crest of the embankment in 2014 may have had some impact on the ultimate trigger, as the embankment was close to failure at this time.

Loading the Upper GLU to failure under predominantly drained conditions also implies the imposition of shear stresses as well as vertical stresses. As shown in Appendix E, Attachment 5, consolidating specimens under a shear stress not only has an effect on available resistance, but also reduces the subsequent tolerable strain to failure. Given the high stresses that acted on the Upper GLU prior to the final construction campaign in 2014, it would have taken only a small additional load to initiate undrained failure, and little incremental deformation. This is consistent with the collapse of the embankment without any apparent warning.

Given the high stresses that acted on the Upper GLU prior to the final construction campaign in 2014, it would have taken only a small additional load to initiate undrained failure, and little incremental deformation. This is consistent with the collapse of the embankment without any apparent warning.

6.3.3 PROGRESSIVE FAILURE

The strength at failure will only be mobilized uniformly if it does not vary with deformation. Failure will begin initially at a position where the local stresses equal the strength. As additional load is applied, yielding spreads to adjacent locations because resistance is limited at locations that have already yielded. This spreading of the yield zone migrates until a failure mechanism develops and unrestrained movement occurs with mobilization of a uniform shear strength.

However, as emphasized in section 5.3, the Upper GLU exhibits strain-weakening behaviour. After yielding has been initiated, the local resistance reduces with increasing load, requiring stress transfer to accommodate not only the influence of additional externally applied load, but also the influence of the reduced capacity of already failed material to resist the applied stresses. The transfer process proceeds to ultimate failure, but the average resistance at ultimate failure is less than the peak resistance.

This process is known as progressive failure. Once progressive failure has been initiated, the development of ultimate collapse can be sudden, depending on the shape of the whole stress-strain relation. As noted in section 6.2.3, the observed sensitivity of the Upper GLU indicates that it might display an ultimate resistance of one-half to one-third of its peak value.

While the mechanics of progressive failure are generally understood, the ability to calculate it is a complex undertaking and is generally reserved for research endeavours or other special studies. Progressive failure analyses have not been undertaken in this study, but Lobbestael et al. (2013) provide a useful overview and example of how progressive failure calculations might be performed. The Panel is of the view that progressive failure was involved in the initiation of collapse of the Perimeter Embankment and subsequent motion. Its influence is embedded in the back-calculated average resistance.

6 | Analysis of Breach Mechanics

6.4 FAILURE MECHANISM

The Panel's Terms of Reference require it to: "report on the cause of the failure of the tailings storage facility at the Mount Polley Mine."

The failure of the tailings storage facility (TSF) was caused by deformation of the Perimeter Embankment that allowed the containment to be breached between survey stations 4+200 and 4+300. The deformation arose because of inadequate resistance of a continuous layer of glaciolacustrine clays (Upper GLU) that existed at about El. 920 m, beneath the overlying till. The GLU deposit had properties that became increasingly contractive when sheared, following consolidation under the applied embankment loads to a normally consolidated state. This made the Upper GLU disposed to undrained failure. Moreover, the Upper GLU exhibited strain-weakening properties when sheared, such that overall resistance of the formation reduced as deformation developed, ultimately overcoming all of the resistance of the stabilizing elements in the section. Hence, the root cause of the breach was the undrained failure of the Upper GLU under the imposed load of the Perimeter Embankment on August 4, 2014.

The root cause of the breach was the undrained failure of the Upper GLU under the imposed load of the Perimeter Embankment on August 4, 2014.

6 | Analysis of Breach Mechanics

6.5 CAUSES OF FAILURE

As outlined in the Terms of Reference, it is expected that the Panel will "identify any technical, management, or other practices that may have enabled or contributed to the mechanism(s) of failure. This may include design, construction, maintenance surveillance and regulation of the facility."

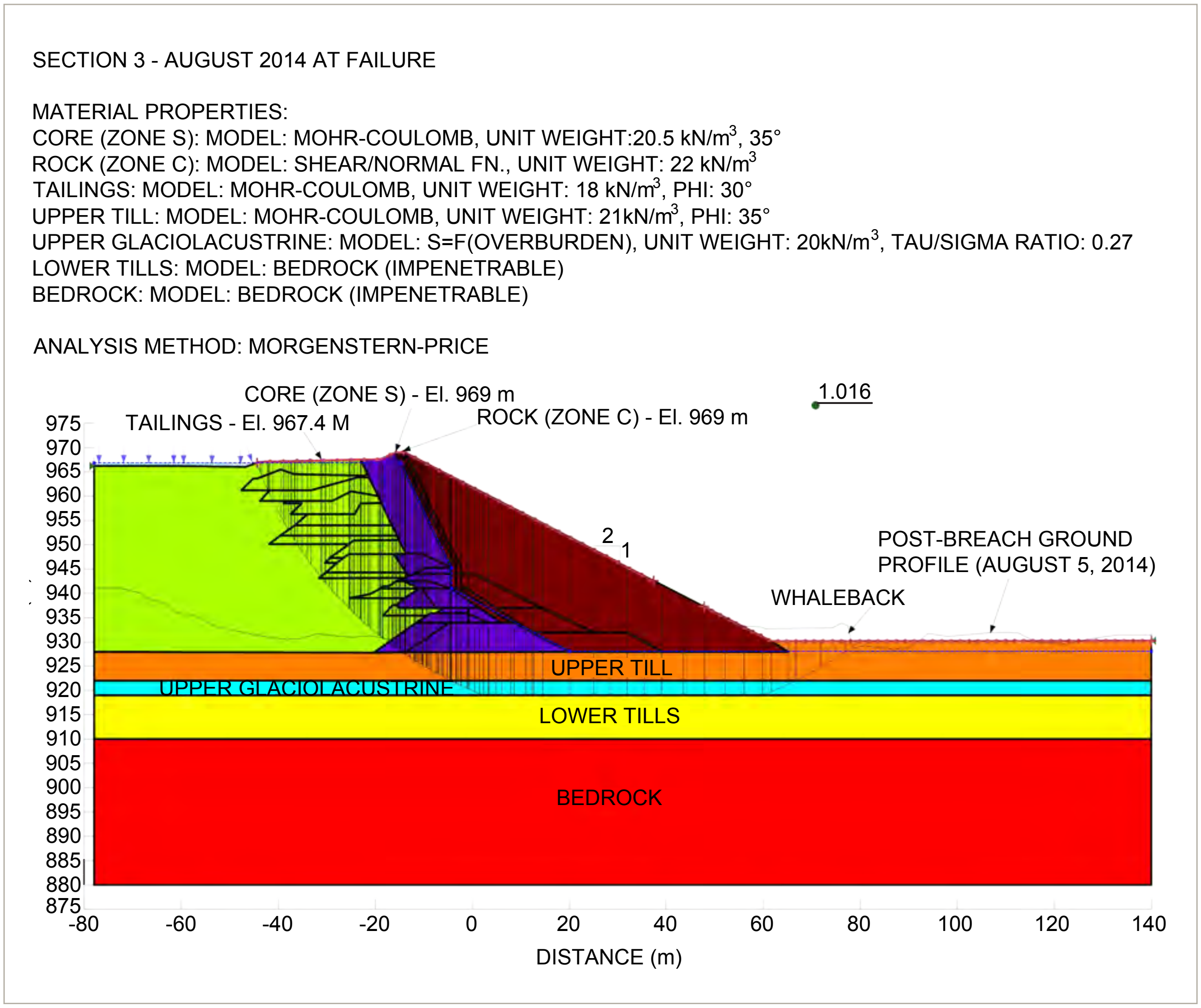
The dominant contribution to the failure resides in its design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous GLU layer in the vicinity of the breach and to recognize that it would be disposed to undrained failure when subjected to the stresses associated with the Dam.

The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation.

At the time of Stage 4 (2006 – 2007), Knight Piésold (KP) had proposed a design for the Perimeter Embankment with a 2H:1V downstream slope and raises of the core and filter with a parallel inclined alignment to El. 965 m. This design has been projected in **Figure 6.5.1** to the core elevation at the time of failure (El. 969 m), and adopting an undrained strength ratio of 0.27 and a high water table, the calculated FS is 1.02. At El. 965 m, the FS is 1.04, much less than the design target of 1.3. Based on the back-calculated undrained strength ratio, the design was doomed to fail.

6 | Analysis of Breach Mechanics

FIGURE 6.5.1: 2-D LIMIT EQUILIBRIUM 2H:1V SLOPE TO ELEVATION 969 M (UNDRAINED STRENGTH RATIO 0.27, HIGH WATER TABLE, FS 1.02)



Hence, the omissions associated with site characterization may be likened to creating a loaded gun. Notwithstanding the large number of experienced geotechnical engineers associated with the TSF over the years, the existence of this loaded gun remained undetected.

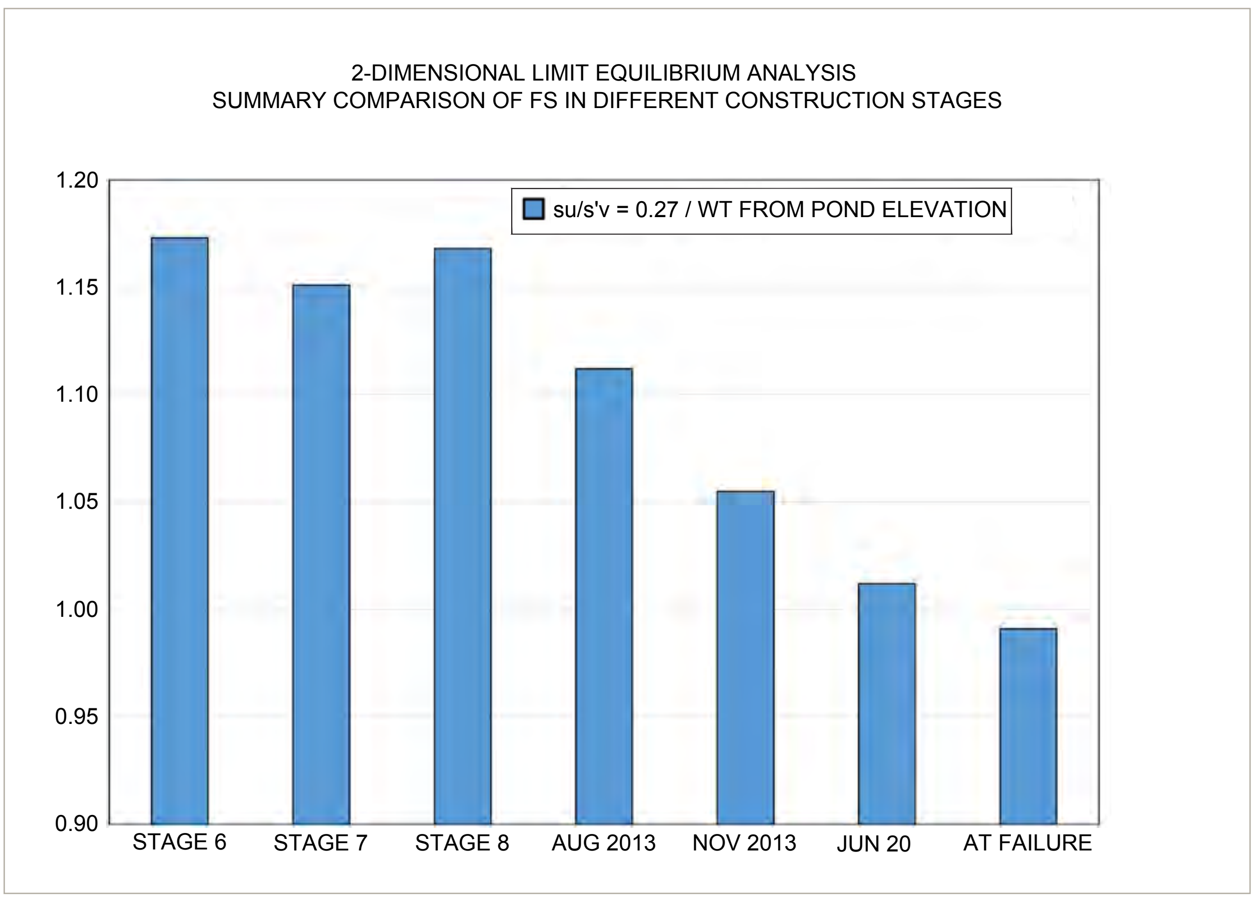
The omissions associated with site characterization may be likened to creating a loaded gun.

6 | Analysis of Breach Mechanics

The lack of recognition of a critical potential failure mode resulted in a misapplication of the Observational Method and, therefore, a false appreciation that the structure was performing as intended during stages of raising. The Observational Method is a powerful tool to manage uncertainty in geotechnical practice. However, it relies on recognition of the potential failure modes, an acceptable design to deal with them, and practical contingency plans to execute in the event observations lead to conditions that require mitigation. The lack of recognition of the critical undrained failure mode that prevailed reduced the Observational Method to mere trial and error.

Figure 6.5.2 shows the variation of the calculated FS with each stage, from Stage 6 to failure, based on the as-built section for each stage. El. 965 m corresponds approximately to the height of the structure at the end of the 2013 construction season. At this stage, the FS is calculated to be only about 1.05, which is similar to the FS for the original design with a 2H:1V slope.

FIGURE 6.5.2: VARIATION IN FS FOR EACH STAGE FROM STAGE 6 TO FAILURE



6 | Analysis of Breach Mechanics

Prior to 2014, the Zone C fill began to be constructed as an angle of repose slope of 1.3H:1V. This appeared to have been an expedient measure and, as illustrated in **Figure 6.5.2**, ultimately resulted in failure of the Perimeter Embankment on August 4, 2014. If constructing unknowingly on the Upper GLU stratum, and not recognizing the potential undrained failure constituted loading the gun, building with a 1.3H:1V angle of repose slope over this stratum pulled the trigger. It appears that the 1.3H:1V slope began as an expedient temporary measure to facilitate construction during Stage 5. It became more or less permanent for subsequent phases, although concerns had been raised before the failure. The circumstances associated with the relative permanency of the 1.3H:1V slope are not well understood by the Panel. The complex issues that prevailed during construction are summarized in section 5.4. **Figure 6.5.3** indicates that, had the downstream slope incorporating the widened crest been flattened to 2H:1V, the FS would have been 1.28. This was close to the required value of 1.3, and the embankment would not have failed. Moreover, the slope of 2H:1V was required, in any case, to support reclamation and closure criteria.

If constructing unknowingly on the Upper GLU...constituted loading the gun, building with a 1.3H:1V angle of repose slope over this stratum pulled the trigger.

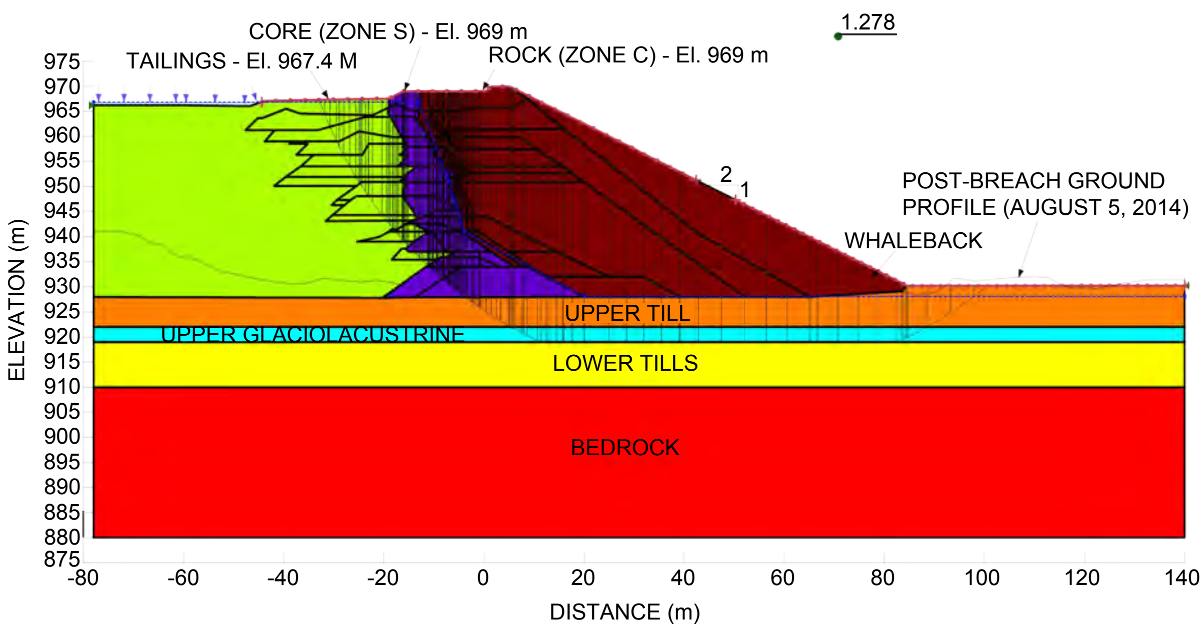
6 | Analysis of Breach Mechanics

FIGURE 6.5.3: PANEL'S STABILITY ANALYSIS FOR 2H:1V SLOPE WITH WIDENED CREST (FS = 1.28)

SECTION 3 - AUGUST 2014 AT FAILURE

MATERIAL PROPERTIES:
CORE (ZONE S): MODEL: MOHR-COULOMB, UNIT WEIGHT:20.5 kN/m^3, 35°
ROCK (ZONE C): MODEL: SHEAR/NORMAL FN., UNIT WEIGHT: 22 kN/m^3
TAILINGS: MODEL: MOHR-COULOMB, UNIT WEIGHT: 18kN/m^3, PHI: 30°
UPPER TILL: MODEL: MOHR-COULOMB, UNIT WEIGHT: 21kN/\m^3, PHI: 35°
UPPER GLACIOLACUSTRINE: MODEL: S=F(OVERBURDEN), UNIT WEIGHT: 20kN/m^3, TAU/SIGMA RATIO: 0.27
LOWER TILLS: MODEL: BEDROCK (IMPENETRABLE)
BEDROCK: MODEL: BEDROCK (IMPENETRABLE)

ANALYSIS METHOD: MORGENSTERN-PRICE



6.6 PREVENTION OF FAILURE

The Terms of Reference (TOR) authorize the Panel to comment on "what actions could have been taken to prevent this failure."

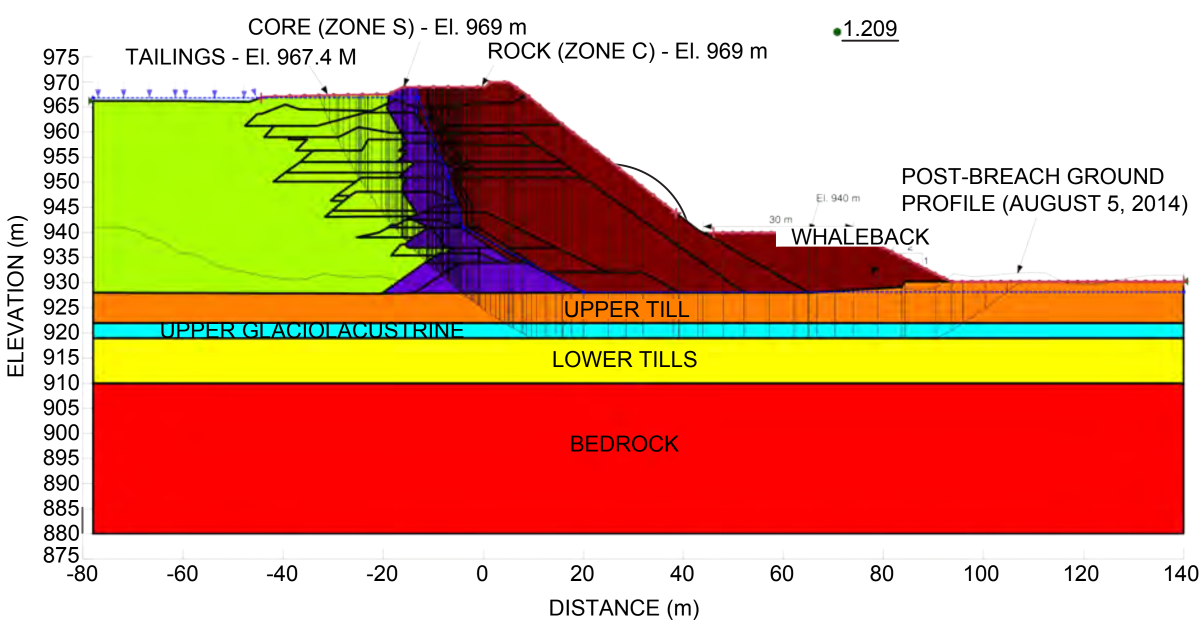
Looking specifically at the failure as documented in section 5.4, it was deemed desirable to increase the target FS to 1.5 since the TSF was operating more or less continually at full capacity. No significant progress to this end was made in Stage 9 before failure occurred. BGC's design report for Stage 10, issued on July 25, 2014, indicated the buttress required to meet the new design objectives that they identified. Had it been in place as shown on **Figure 6.6.1**, the FS would have been 1.2 and the failure would have been prevented.

FIGURE 6.6.1: PANEL STABILITY ANALYSIS FOR BGC BUTTRESS ON STAGE 9

SECTION 3 - AUGUST 2014 AT FAILURE

MATERIAL PROPERTIES:
CORE (ZONE S): MODEL: MOHR-COULOMB, UNIT WEIGHT:20.5 kN/m^3, 35°
ROCK (ZONE C): MODEL: SHEAR/NORMAL FN., UNIT WEIGHT: 22 kN/m^3
TAILINGS: MODEL: MOHR-COULOMB, UNIT WEIGHT: 18 kN/m^3, PHI: 30°
UPPER TILL: MODEL: MOHR-COULOMB, UNIT WEIGHT: 21kN/m^3, PHI: 35°
UPPER GLACIOLACUSTRINE: MODEL: S=F(OVERBURDEN), UNIT WEIGHT: 20kN/m^3, TAU/SIGMA RATIO: 0.27
LOWER TILLS: MODEL: BEDROCK (IMPENETRABLE)
BEDROCK: MODEL: BEDROCK (IMPENETRABLE)

ANALYSIS METHOD: MORGENSTERN-PRICE



7 | Management Practices

The Panel is cognizant that management practices have had a significant influence on the design, construction and operation of the tailings storage facility (TSF). For example, the Panel has already drawn attention to water balance protocols and the growth of water inventory in the TSF due to the timing associated with the implementation of water treatment and discharge. It has pointed out that the recurrent adoption of a 1.3H:1V downstream slope for the Perimeter Embankment may have been due to limited material availability or other aspects related to mine planning. The details are not clear. What is clear is that multiple changes were made in the section of the dam in response to the limited time horizons adopted in mine and water planning.

The Panel has been advised that Mount Polley Mining Corporation (MPMC) were in the midst of becoming Mining Association of Canada (MAC) compliant and that tailings management issues were reported to the Board of Directors. It has not identified any flaws in this reporting structure.

However, in conducting its inquiry, the Panel limited itself to relying on interviews and on the documents that it received from the various stakeholders, which were sufficient to determine root cause of the breach. The Panel did not conduct its process according to formal legal procedures. To do so would have extended the length of this investigation and would have entered into an assessment of roles and responsibilities, which is beyond the Panel's authorization. As a result, the Panel is not able to offer an adequate assessment of the role of management and oversight in its contribution to the cause of the failure. In particular, the Panel has not explored the relationship between the designers and owner, contractual or otherwise. Accordingly, the Panel is unable to ascertain the circumstances that contributed to key decisions.

8 | Regulatory Oversight

8.1 ROLES AND RESPONSIBILITIES

This section describes the regulatory roles and responsibilities for impoundments and diversions at mines in B.C. A Memorandum of Understanding (MOU) is in place between the Ministry of Energy and Mines (MEM), the Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) and the Ministry of the Environment (MoE) to clarify the regulation of these facilities. This MOU and other documents related to Mine Tailings are available on the Geotechnical page of the MEM website:

http://www.empr.gov.bc.ca/MINING/PERMITTING-RECLAMATION/GEOTECH/Pages/default.aspx

The MOU clearly places the responsibility for the engineering aspects of the Mount Polley tailings storage facility (TSF), seepage collection ponds and diversions on the shoulders of MEM, while the water quality of any discharges is the responsibility of MoE. Two permits are in place for the TSF and associated facilities: Permit M-200 from MEM and Permit 11678 from MoE.

MEM permits are issued by the Chief Inspector of Mines of B.C. The Manager of Geotechnical Engineering and the Manager Environmental report to the Deputy Chief Inspector of Mines, Permitting. The Manager Geotechnical Engineering has a staff of two geotechnical engineers and one reclamation specialist, while the Manager Environmental has a staff of three geoscientists. This staff of eight is responsible for inspection of operating mines and permitting of new mines in B.C. Apart from TSF-related activities, they also have regulatory responsibility for open pits, underground workings, and mined rock and overburden piles. The Geotechnical Manager and staff also participate in secondary activities including the Canadian Dam Association (CDA) Regulatory Committee and coordination with the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) in development of the *Professional Practice Guidelines for Dam Safety Reviews* for mining dams in B.C.[1] The latter publication is available on the above-mentioned website.

The ongoing activities of the geotechnical staff include:

- Review of geotechnical aspects of proposed mining projects in the Environmental Assessment process.
- Review of geotechnical aspects of *Mines Act* Permit applications during the approval and permit conditions development process.
- Review of permit amendment applications for dam raises, mine expansions, etc.
- Geotechnical site inspections of operating and closed mines.
- Review of geotechnical reports submitted under the Code, including annual dam safety inspections for mining dams and diversions.

8 | Regulatory Oversight

Filling the positions at MEM has been challenging at times. The present Manager of Geotechnical Engineering joined MEM in October 2011 following a period of over 3 years when the position was open. A senior geotechnical position was made redundant in 2003, but a new geotechnical inspector position was created in 2007. This position was also vacant for about 2 years until filled in September 2012. A third position was posted in May 2014 and filled in early October 2014. To attract qualified personnel, MEM has to compete with industry salaries, which is a challenge, especially during a booming mining cycle. To help accomplish these tasks, MEM has appointed four consulting professional engineers as Contract Inspectors to inspect tailings dams and other mining facilities.

An annual inspection schedule is developed for all the inspectors. The target is to inspect about 30 mines on an annual basis. Mount Polley is one of these mines.

8.2 REGULATORY INTERACTIONS RELATED TO MOUNT POLLEY MINING CORPORATION (MPMC) TAILINGS STORAGE FACILITY (TSF)

Table 8.2.1 lists the dates of the geotechnical inspections completed at Mount Polley from 1995 to 2014. Annual inspections were completed during the Phase 1 operations and were resumed after start-up of Phase 2 operations until 2008. There were no geotechnical inspections during 2009, 2010 and 2011, which is the same period as the vacancy of the Geotechnical Manager's position.

TABLE 8.2.1: GEOTECHNICAL INSPECTIONS AT MOUNT POLLEY

DATE OF INSPECTION	TYPE OF INSPECTION PERFORMED	INSPECTOR
Sept 20, 1995	Geotechnical	G. Headley
Oct 19, 1995	Geotechnical	G. Headley
Oct 19, 1995	Geotechnical	C. Brawner
July 9 and 13, 1996	Geotechnical	G. Headley
Aug 26, 1996	Geotechnical	G. Headley
Sep 27–28, 1996	Geotechnical	G. Headley
May 27, 1997	Geotechnical	G. Headley
Jun 4, 1998	Geotechnical	G. Headley
Jun 17, 1999	Geotechnical	G. Headley
Aug 17, 2000	Geotechnical	G. Headley
April 25, 2001	Geotechnical	C. Carr
Feb 3, 2005	Geotechnical	C. Carr
Oct 13, 2005	Geotechnical	N. Rose
Aug 30, 2006	Geotechnical	N. Rose
July 31, 2007	Geotechnical	N. Rose
Jun 7, 2008	Geotechnical	D. Apel
Apr 12, 2012	Geotechnical – site visit	G. Warnock
Sept 24, 2012	Geotechnical	M. Cullen
Sept 13, 2013	Geotechnical	M. Cullen
Dec 4, 2014	Geotechnical	M. Cullen

8 | Regulatory Oversight

Most of the inspection reports did not identify any concerns with the TSF, except in the following cases. Based on the inspection of April 25, 2001 the inspector observed: *"The Ministry would strongly support the installation of two slope inclinometers at the downstream toe buttress to monitor potential dam and/or foundation movement. The slope inclinometers should extend through the underlying glaciolacustrine sediments."* [2] MPMC responded that this matter was forwarded to Knight Piésold (KP). [3] These inclinometers were installed in July 2001 (refer to Appendix F).

On October 13, 2005, [4] narrow beach widths were observed on the southwest side of the pond. On August 30, 2006, [5] wide beach widths were observed and MEM requested a specific specification for beach width. MPMC responded, quoting KP: [6] *"The tailings embankments have been designed to remain stable for any condition and therefore there is not a 'requirement' for a minimum beach width in terms of embankment performance."*

On July 31, 2007, [7] the inspection found two concerns that were Departures from Approval. First, Zone S material contained particles as large as 12 inches, which had to be removed to satisfy the specification of 4 inches. In addition, there was no beach in the vicinity of the southeast corner and MPMC was told that the beach must be re-established and that more frequent monitoring of the piezometers must be conducted in that area.

While the examples above illustrate the role of the Regulator in matters of construction and performance, the Regulator also reviewed design. The following design-related issues were brought up by the Regulator:

- The shear strength associated with the lacustrine materials in the well log GW96-1A. [8]
- Testing on residual strength. [9, 10]
- Need to migrate factor of safety (FS) from 1.3 to 1.5. [11]

In each case, the Engineer of Record (EOR) responded to the inquiries and these instances illustrate the limited ability of the Regulator to influence the design issues.

8 | Regulatory Oversight

8.3 PANEL ASSESSMENT

The roles and responsibilities of the Ministry of Energy and Mines (MEM) to regulate impoundments and diversions at mines are well defined and agreed upon with other Ministries. Within MEM, the roles and responsibilities of the geotechnical engineering group responsible for regulating the design, construction and operational aspects of TSFs are also clearly defined. This small group of professionals covers a large portfolio of existing facilities, permitting of new facilities and environmental assessments for proposed projects.

The Panel finds that the MEM Geotechnical Staff and the Contract Inspectors are well qualified to perform their responsibilities. The team is well organized and has clear targets and schedules for annual inspections. The Panel considers the technical qualifications of the MEM Geotechnical Staff as among the best that it has encountered among agencies with similar duties.

MEM geotechnical engineers addressed significant issues during the reviews and inspections of the Mount Polley TSF. They had insightful questions for the designers at many instances during their review of the design documents, as noted above. The EOR responded to these questions based on their observations and understanding of site conditions. The EOR is responsible for the overall performance of the structure as well as the interpretation of site conditions. The Regulator has to rely on the expertise and the professionalism of the EOR as the Regulator is not the designer.

Despite having a strong regulatory process and personnel, the Perimeter Embankment of the Mount Polley TSF still failed. As indicated in earlier sections, it was a sudden failure without precursors. Additional inspections of the TSF would not have prevented the failure.

However, the question remains as to the expectations from the Regulator in the future. The relationship between the Regulator and the EOR can result in different opinions being expressed that are not easy to resolve without independent input. In such circumstances, independent external advice could be sought as further described in section 9.0. There is a difference between regulating construction and regulating design after it has been approved. The Regulator by observation and experience has the capacity to regulate construction but does not have the capacity to modify the design. Regulators are not normally recruited with specific dam design experience and are limited by statute in their capacity to take on design responsibilities. This role resides with the EOR.

8 | Regulatory Oversight

It is difficult to review the adequacy of a constructed facility without having limits of measurable indicators that define its performance. Measurable indicators of safe and orderly design and construction are needed for all existing and future tailings facilities that can be monitored and interpreted to evaluate this performance. Section 9.0 provides further elaboration of Quantitative Performance Objectives (QPOs) as a means of accomplishing this.

ENDNOTES

1) Panel Interview, 12/12/14.
2) MP00170
3) MP00218
4) MP00174
5) MP00175
6) MP00216
7) MP00177
8) MO00137
9) MP00139
10) MO00222
11) MP00187

9 | Where Do We Go From Here?

9.1 PERFORMANCE OF B.C. TAILINGS DAMS

Central to the Panel's Terms of Reference (Appendix A) is to recommend actions for preventing future tailings dam failures:

"... *the Panel may make recommendations to government on actions that could be taken to ensure that a similar failure does not occur at other mine sites in B.C.*"

Fulfilling this mandate starts by considering the tailings dams that currently exist in the province. In particular, this involves how many there are and how they have performed. Appendix I describes the Panel's efforts in this respect. It found that there are currently 123 active tailings dams, those that contain surface water in their impoundments along with tailings.

Active tailings dams were tracked through the years from Ministry of Energy and Mines (MEM) records. In the 46-year period since 1969, there was a total of 4,095 years of active operation and 7 failures, where failure is considered to be breach of the dam resulting in release of tailings and/or water. This corresponds to a failure frequency of 1.7×10^{-3} per dam per year. In other words, statistically there is approximately a 1-in-600 chance of a tailings dam failure in any given year, based on historical performance over the period of record.

While these numbers may seem small, their implications are not. If the inventory of active tailings dams in the province remains unchanged, and performance in the future reflects that in the past, then on average there will be two failures every 10 years and six every 30. In the face of these prospects, the Panel firmly rejects any notion that business as usual can continue.

The Panel firmly rejects any notion that business as usual can continue.

9 | Where Do We Go From Here?

9.2 GETTING TO ZERO

In risk-based dam safety practice for conventional water dams, some particular level of tolerable risk is often specified that, in turn, implies some tolerable failure rate. The Panel does not accept the concept of a tolerable failure rate for tailings dams. To do so, no matter how small, would institutionalize failure. First Nations will not accept this, the public will not permit it, government will not allow it, and the mining industry will not survive it.

Clearly, improvements to current practice provide an essential starting point on the path to zero failures. But the Panel's evaluation of portfolio risk shows that incremental changes will not be sufficient to achieve this objective.

The path to zero needs an added dimension, and that dimension is technology.

Appendix I explains why. Ultimately, the problem stems from how many active tailings dams there are in the province. To ensure against future failures for all of them would require roughly a hundredfold reduction or more in the current failure frequency. While advances in practices, procedures and policies are imperative, the Panel does not expect these measures by themselves to achieve this degree of improvement. The path to zero needs an added dimension, and that dimension is technology.

Tailings dams are complex systems that have evolved over the years. They are also unforgiving systems, in terms of the number of things that have to go right. Their reliability is contingent on consistently flawless execution in planning, in subsurface investigation, in analysis and design, in construction quality, in operational diligence, in monitoring, in regulatory actions, and in risk management at every level. All of these activities are subject to human error.

Failures invariably bring about improvements in technology that help compensate for human error.

Human error is often, if not always, found to play a key role in technological failures. And human error will always be with us, as much as we might wish it to be otherwise. This is why failures invariably bring about improvements in technology that help compensate for human error. In perhaps the most notorious containment failure, double-hulled tankers were mandated after the *Exxon Valdez* oil spill. Similarly, improvements to rail tank cars are being adopted in the wake of the Lac-Mégantic tragedy. But tailings dams have no such redundancies. Without exception, dam breaches produce tailings releases. This is why best practices can only go so far in improving the safety of tailings technology that has not fundamentally changed in the past hundred years.

9 | Where Do We Go From Here?

Improving technology to ensure against failures requires eliminating water both on and in the tailings: water on the surface, and water contained in the interparticle voids. Only this can provide the kind of failsafe redundancy that prevents releases no matter what. In terms of portfolio risk, Appendix I shows that this works by reducing the inventory of active tailings dams subject to failure in the first place. Simply put, dam failures are reduced by reducing the number of dams that can fail.

Thus, the path to zero leads to best practices, then continues on to best technology.

9.3 BEST AVAILABLE TAILINGS TECHNOLOGY

9.3.1 BAT PRINCIPLES

While best practices focus on the performance of the tailings dam, best available technology (BAT) concerns the tailings deposit itself. The goal of BAT for tailings management is to assure physical stability of the tailings deposit. This is achieved by preventing release of impoundment contents, independent of the integrity of any containment structures. In accomplishing this objective, BAT has three components that derive from first principles of soil mechanics:

1. **Eliminate surface water from the impoundment.**
2. **Promote unsaturated conditions in the tailings with drainage provisions.**
3. **Achieve dilatant conditions throughout the tailings deposit by compaction.**

The first of these, eliminating surface water, not only precludes release of water itself, but also eliminates fluvial tailings transport mechanisms like those illustrated in Appendix C during the Mount Polley breach. The second, promoting unsaturated conditions by drainage, reduces the possibility for, and the quantity of, high-mobility flowslide release of tailings. And the third, achieving dilatant conditions by compaction, further reduces flowslide potential by improving the properties of the tailings mass. Thus, underpinning these principles are multiple redundancies that provide defence in depth.

The Panel recognizes that eliminating water from the tailings deposit will not eliminate the need for storage of mine and processing water elsewhere. But Mount Polley has shown the intrinsic hazards associated with dual-purpose impoundments storing both water and tailings. The Panel considers that security can be more readily assured for conventional water dams that are designed and constructed for their own purpose and that preventing tailings release is the overriding imperative.

9 | Where Do We Go From Here?

9.3.2 BAT METHODS

The overarching goal of BAT is to reduce the number of tailings dams subject to failure. This can be achieved most directly by storing the majority of the tailings below ground—in mined-out pits for surface mining operations or as backfill for underground mines. Both methods require integrating tailings planning into mine planning. This has not been common practice in the industry to date, as the Mount Polley case has shown, and the synergies to be achieved are mostly unexplored. Apart from this, surface storage using filtered tailings technology is a prime candidate for BAT.

The overarching goal of BAT is to reduce the number of tailings dams subject to failure.

Demonstrated technology for producing and placing filtered tailings (sometimes termed "dry stack" tailings) is well-known in the industry. Its adoption and design practices are documented in the literature.[1, 2] Using various kinds of equipment, the water content of the tailings is reduced before they leave the mill. The specified degree of water removal can vary, but is sufficient to allow transport by truck or conveyor to the tailings facility and compaction. Compaction is necessary to prevent liquefaction flowslides that can and have occurred in loosely placed dewatered materials due to infiltration of ponded surface runoff. The Panel recognizes that creating dry tailings may increase the amount of water requiring treatment or storage.

Filtered tailings technology embodies all three BAT components described in section 9.3.1. Most commonly used in dry climates where economy in water consumption is important, it has also been adapted to cold regions.[3] This method has been used since start-up of the Greens Creek mine in Alaska under conditions not unlike coastal B.C.[4] The Greens Creek facility is shown in **Figure 9.1.1**.

Variations on this technology are easily envisioned, for example separation, dewatering, and gravity drainage of sand tailings by cycloning to reduce quantities requiring filtration dewatering. The Panel believes that additional enhancements are ripe for development if there is incentive to do so.

In some cases, clayey ore may pose difficulties in dewatering. And most filtered tailings operations to date have been relatively small. But some new operations will be producing filtered tailings at a rate of 68,000 tonnes per day—almost three times the production of Mount Polley—in facilities that will reach heights of 150 metres (m). As demonstrated by the Greens Creek case and others, there are no overriding technical impediments to more widespread adoption of filtered tailings technology.

There are no overriding technical impediments to more widespread adoption of filtered tailings technology.

9 | Where Do We Go From Here?

FIGURE 9.1.1 FILTERED TAILINGS FACILITY, GREENS CREEK, ALASKA

The chief reason for the limited industry adoption of filtered tailings to date is economic. Comparisons of capital and operating costs alone invariably favour conventional methods. But this takes a limited view. Cost estimates for conventional tailings dams do not include the risk costs, either direct or indirect, associated with failure potential. The Mount Polley case underscores the magnitude of direct costs for cleanup, but indirect losses—notably in market capitalization—can be even larger.[5] Nor do standard costing procedures consider externalities, like added costs that accrue to the industry as a whole, some of them difficult or impossible to quantify. Full consideration of life cycle costs including closure, environmental liabilities, and other externalities will provide a more complete economic picture. While economic factors cannot be neglected, neither can they continue to pre-empt best technology.

While economic factors cannot be neglected, neither can they continue to pre-empt best technology.

9 | Where Do We Go From Here?

9.3.3 BAT FOR CLOSURE

Closure of tailings deposits is subject to two fundamental considerations: physical stability and chemical stability. Although the former is the object of the Panel's investigation, no treatment of tailings technology can ignore the latter. Matters related to physical and chemical stability reside in different domains and have developed independently, each with their own goals and methods. These two aspects converge in the context of BAT.

In short, the most serious chemical stability problem concerns tailings that contain sulfide minerals, particularly in metal and coal mining. In the presence of oxygen, these sulfides react to produce acid that then mobilizes a variety of metals in solution. There are a number of ways to arrest this reaction, and one is to saturate the tailings so that water replaces oxygen in the void spaces. This saturation is most conveniently achieved by maintaining water over the surface of the tailings. Hence, so-called water covers have sometimes been adopted for reactive tailings during operation and for closure.

It can be quickly recognized that water covers run counter to the BAT principles defined in section 9.3.1. But the Mount Polley failure shows why physical stability must remain foremost and cannot be compromised. Although the tailings released at Mount Polley were not highly reactive, it is sobering to contemplate the chemical effects had they been. No method for achieving chemical stability can succeed without first ensuring physical stability: chemical stability requires above all else that the tailings stay in one place.

Filtered tailings technology adopts a different approach to chemical stability. Rather than arresting the reaction, it retards the transport of reaction products. Seepage gradients are greatly diminished by eliminating surface water. This has a beneficial effect not only on sulfide reaction products; it also equally reduces transport of soluble constituents such as arsenic, sulfates and selenium, if present in the tailings.

Moreover, the technology for alternative dry covers is well advanced. Using different cover designs for different climatic conditions, soil covers placed over the tailings deposit further reduce infiltration, retard oxygen entry, or both. Cover placement and reclamation can proceed concurrently with operation, as shown in the foreground in **Figure 9.1.1** at Greens Creek.

Yet other technologies attack the chemical effects of sulfide minerals by removing them from the tailings. Doing so using conventional metallurgical processes has been shown to be technically and economically feasible.[6] These same techniques can be used, in effect, to manufacture clean tailings cover material free from sulfides.[7]

This shows that the physical stability objectives of BAT are not incompatible with chemical stability. A variety of complementary technologies are available for achieving both.

9.3.4 BAT RECOMMENDATIONS

Implementation of BAT is best carried out using a phased approach that applies differently to tailings impoundments in various stages of their life cycle.

- **For existing tailings impoundments**. Constructing filtered tailings facilities on existing conventional impoundments poses several technical hurdles. Chief among them is undrained shear failure in the underlying saturated tailings, similar to what caused the Mount Polley incident. Attempting to retrofit existing conventional tailings impoundments is therefore not recommended, with reliance instead on best practices during their remaining active life.
- **For new tailings facilities**. BAT should be actively encouraged for new tailings facilities at existing and proposed mines. Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor.
- **For closure**. BAT principles should be applied to closure of active impoundments so that they are progressively removed from the inventory by attrition. Where applicable, alternatives to water covers should be aggressively pursued.

As discussed in section 9.2, best technology is only one of the two components necessary for safety improvement. The complementary aspects of best practices are presented in the following sections.

9 | Where Do We Go From Here?

9.4 BEST APPLICABLE PRACTICES (BAP)

The safety of any dam, water or tailings, relies on multiple levels of defence. The Panel was disconcerted to find that, while the Mount Polley Tailings Dam failed because of an undetected weakness in the foundation, it could have failed by overtopping, which it almost did in May 2014. Or it could have failed by internal erosion, for which some evidence was discovered. Clearly, multiple failure modes were in progress, and they differed mainly in how far they had progressed down their respective failure pathways.

Accordingly, recommendations for future BAP require considerations that go beyond stability calculations. It is important that safety be enhanced by providing for robust outcomes in dam design, construction and operations. As discussed below, this has implications for corporate responsibility, enhanced regulatory capacity, expanded technical review, and improvements in professional practice.

It is important that safety be enhanced by providing for robust outcomes in dam design, construction and operations.

9.4.1 CORPORATE GOVERNANCE

In response to several international tailings dam failure incidents in the 1990s, the Mining Association of Canada (MAC) established a task force in 1996 to promote safe, environmentally responsible management of tailings and mine waste. The task force concluded that the main priority should focus on improvement of tailings management, which resulted in the establishment of the MAC Tailings Working Group. The outcome of this initiative were several guides related to the management of tailings facilities; the development of operations, maintenance and surveillance manuals; and auditing and assessment of tailings management facilities.[8] The guides themselves are available from the MAC.[9] They are now embraced by the Towards Sustainable Mining (TSM) initiative launched by MAC in 2004.

Compliance with the TSM initiative is an element of BAP for the mining industry today. Accordingly, mining operations in B.C. proposing to operate a tailings storage facility (TSF) should either be required to be a member of MAC—ensuring adherence to the TSM—or be obliged to commit to an equivalent program, including the audit function. Tailings management is often not a core skill in many mining organizations. Embracing MAC's TSM initiative will ensure awareness of responsibilities at the highest corporate levels.

9 | Where Do We Go From Here?

At the same time, many in the industry have reacted to the Mount Polley failure with incredulity, asking how it could have happened with programs such as MAC's in place. This serves as a reminder that these programs should not instill a sense of overconfidence and cannot themselves be seen as a substitute for more fundamental changes in technology.

9.4.2 CORPORATE TSF DESIGN RESPONSIBILITIES

In the experience of the Panel, TSF design studies submitted to Regulators are often lacking in detail regarding the factors that need to be considered in assuring safety of the facility. This applies equally to appropriate tailings technology and to performance metrics for confirming orderly construction and operations.

At Mount Polley, the only quantitative performance objectives were those implied in its design criteria. A list of potential failure modes was compiled in the 2006 Dam Safety Report, but these were generic and not tied to specific site conditions. One of the lessons learned here is that future permit applications for TSFs must provide a more comprehensive assessment of potential geotechnical problems associated with the selected site. In addition, BAT for both tailings storage and closure considerations also needs to be incorporated in such proposals.

The Panel is of the view that the inclusion of these considerations and the declaration of Quantitative Performance Objectives (QPOs) are best incorporated early in project commitment at the bankable feasibility level. QPOs are intended to constrain the type of ad hoc design practices that characterized Mount Polley and strengthen regulatory capacity.

The Panel would require a bankable feasibility study and related permit application to have considered all technical, environmental, social and economic aspects of the project. Resolution of technical and environmental considerations would usually be supported by proven methods, although technology development studies would not be precluded if they have advanced far enough to warrant implementation in practice. The bankable feasibility study would be of sufficient detail to support an investment decision that might have an accuracy of ±10%–15%.

9 | Where Do We Go From Here?

More explicitly, the bankable feasibility document would be required to contain the following:

1) A detailed evaluation of all potential failure modes associated with:

   - The geological conditions of the site
   - The uncertainties associated with this evaluation
   - The role of the Observational Method to manage residual risk
   - Mitigation measures in case worse than anticipated conditions are encountered.

   This evaluation should be updated and incorporated into MEM requirements for annual inspection and construction review. This is to ensure that the evaluation would become a living document maintained throughout the life of the facility. It should be sufficiently well documented to survive changes in mine personnel, mine ownership or Engineers of Record (EORs), and it should be referenced as part of the Operations Maintenance and Surveillance (OMS) manual. The Panel anticipates that as-built reports would provide the basic information recording departures from what had been anticipated. An ongoing compilation should be maintained by the EOR as a separate document.

2) Detailed cost analyses of BAT tailings and closure options, so that alternative means of achieving BAT can be understood and accommodated. As discussed in section 9.3.2, this assessment should recognize that indirect and unquantifiable costs cannot be fully incorporated and hence the results of the cost analyses should not supersede BAT safety considerations.

3) A detailed declaration of QPOs, beyond those associated with regulatory compliance and ordinary design criteria. Examples of QPOs are numerical values and limits associated with:

   - Beach widths
   - Calibration of impoundment filling schedule
   - Water balance audits and calibration
   - Construction material availability and scheduling to ultimate height of structure
   - Instrumentation adequacy and reliability
   - Trigger levels for response to instrumentation
   - Performance data gathering, interpretation, and reporting intervals

9 | Where Do We Go From Here?

The Panel recognizes the need for a regulatory process that is responsive to changed conditions arising from market forces, reserves, regulatory revisions and technical issues. It is envisaged that such changes can be accommodated by staged approval for construction, as occurs at present. However, the stage applications should honour the declared QPOs or present a basis for their modification.

The Panel recognizes the need for a regulatory process that is responsive to changed conditions arising from market forces, reserves, regulatory revisions and technical issues.

9.4.3 INDEPENDENT TAILINGS REVIEW BOARD (ITRB)

The appointment of ITRBs to provide third-party advice on the design, construction, operation and closure has become increasingly common and is recognized to provide value.[10] The World Bank and other lenders groups are requiring the formation of an ITRB. International Finance Corporation/World Bank guidance and operating principles OP4.01 and OPR.37 establish the requirement to review the development of tailings dam design, construction and initial dam filling. Maintaining an ITRB through operations and closure will depend upon the scale and complexity of the facility. Some large corporations retain a third-party review board for ongoing advice on tailings operations to complement their internal technical audit systems.

The appointment of ITRBs to provide third-party advice on the design, construction, operation and closure has become increasingly common and is recognized to provide value.

ITRBs are not unique to the mining industry. They have a long history in water dam design and safety assessments. In British Columbia, BC Hydro has considerable experience with such Boards for safety assessment of both existing and new dam projects. In a mining context, an ITRB could be asked to provide opinions on the following:

- Whether the design, construction and operation of the TSF are consistent with satisfactory long-term performance.
- Whether design and construction have been performed in accordance with the Board's expectation of good practice.
- Whether safety and operation of the TSF conform to the Board's expectation of good practice.
- Whether there are weaknesses that would reasonably be expected to have a material adverse effect on the integrity of the TSF, human health, safety, and successful operation of the facility for its intended purpose.

9 | Where Do We Go From Here?

Experience has shown that the effectiveness of an ITRB in specific circumstances depends on the following:

- That it not be used exclusively as a means for obtaining regulatory approval.
- That it not be used for transfer of corporate liability by requesting indemnification from Board members.
- That it be free from external influence or conflict of interest.
- That there be means to assure that its recommendations are acted upon.

No ITRB can function successfully without unqualified support and commitment at the highest corporate levels. While it is essential that the Board be organized by Mine Operations, it is equally essential that its reports go to senior corporate management and Regulators. To establish and strengthen credibility, Board reports should also be open to other stakeholders. An important mechanism for accountability in response to Board recommendations is the creation of an Action Log that reviews corporate response to Board recommendations at each successive meeting.

No ITRB can function successfully without unqualified support and commitment at the highest corporate levels.

It is evident that the establishment of Independent Tailings Review Boards is an element of BAP, and the Panel is of the view that they have a role in improving current practice. But they should not be necessary for all tailings undertakings and MEM should consider, based on their current portfolio of operating and proposed TSFs, the conditions related to complexity and failure consequence that warrant an ITRB.

9 | Where Do We Go From Here?

9.4.4 MINISTRY OF ENERGY AND MINES (MEM)

As noted in section 7, the Panel was favourably impressed by the skill and commitment of MEM's geotechnical staff in carrying out their responsibilities. Nevertheless, it also considered what measures could be taken to improve regulatory operations.

With recent inspections of TSFs in the province in hand, the short-term need is to evaluate these facilities with respect to the following potential failure modes, in order of importance:

1. **Undrained shear failure** for dams with silt and clay foundation soils.
2. **Water balance adequacy,** including provisions and contingencies for wet years.
3. **Filter adequacy,** especially for dams containing broadly graded soils or mine waste.

The Regulator is not the designer.

One issue identified in section 8.0 is the ultimate reliance of the Regulator on the EOR to confirm that the facility is safe and is operating as intended. The Regulator is not the designer, and this limits the degree of inquiry that is manageable. If Regulators were provided with more information in an ongoing manner, they would be better versed to engage the EOR. This is one of the benefits of having declared QPOs that can be monitored, as discussed in section 9.4.2. To this end, MEM should evaluate how to determine the QPOs associated with ongoing facilities and begin to apply them in practice.

Additionally, the Panel's compilation of the province's tailings dam inventory revealed limitations in MEM's capacity for information retrieval, especially for timely response to unexpected occurrences. Tailings dam data for each mine and each structure needs to be scanned electronically, compiled separately from permit files, and maintained in a readily accessible database.

9.4.5 PROFESSIONAL PRACTICE

The Panel found it disconcerting that, notwithstanding the large number of experienced geotechnical engineers associated with the Mount Polley TSF, the overall adequacy of the site investigation and characterization of ground conditions beneath the Perimeter Embankment went unquestioned. This may reflect a regional issue, or possibly one of wider extent. Regardless, it calls for a concerted effort to improve professional practice in this area. The situation is reminiscent of the conditions that prevailed in B.C. that resulted in the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) Guidelines for *Legislated Landslide Assessment for Proposed Residential Developments in B.C.*

In the view of the Panel, the fundamental need is to improve the geological, geomorphological , hydrogeological and possibly seismotectonic understanding of sites proposed for tailings dams in B.C. This improved understanding should account for the likely scale associated with variability so that site investigations can be planned with enhanced reliability.

APEGBC appears to be well-suited for this task.

9.4.6 CANADIAN DAM ASSOCIATION (CDA) GUIDELINES

From its inception in 1995, the Mount Polley TSF adopted a minimum factor of safety (FS) of 1.3 during operations and 1.5 for closure. As chronicled in section 5.4, these FS criteria drove key decisions throughout the design process, and so the Panel is of the view that it would be helpful to comment on them.

CDA dam safety guidelines originally developed for water dams were subsequently adapted to tailings dams, with target factors of safety as indicated in **Table 9.4.1**.[11]

TABLE 9.4.1 TARGET FACTORS OF SAFETY FOR SLOPE STABILITY IN CONSTRUCTION, OPERATION AND TRANSITION PHASES – STATIC ASSESSMENT (AFTER CDA, 2014)

LOADING CONDITIONS	MINIMUM FACTOR OF SAFETY	SLOPE
During or at end of construction	>1.3 depending on risk assessment during construction	typically downstream
Long-term (steady state seepage, normal reservoir level)	1.5	downstream

9 | Where Do We Go From Here?

These 2014 guidelines vest responsibility for establishing appropriate FS criteria solely with the designer, subject to the designer's consideration of the following:

- The consequences of failure
- The loading conditions
- The strength parameters used

Hence, the CDA Guidelines are premised on proper evaluation of these factors. But in the case of Mount Polley, this premise was flawed. Few would argue that the failure consequences were anything less than catastrophic to those affected. The loading conditions did not account for the development of normally consolidated conditions in the foundation. And the strength parameters neglected undrained shearing. Furthermore, selection of FS criteria using risk analysis, as specified in **Table 9.4.1**, could not have succeeded because the operative failure mode went unrecognized.

Mount Polley illustrates that dam safety guidelines intended to be protective of public safety, environmental and cultural values cannot presume that the designer will act correctly in every case. To do so defeats the purpose of FS criteria as a safety net. In this, the CDA Guidelines are unable to achieve their intended purpose. Neither is the Province well served, to the extent that MEM has incorporated compliance with these guidelines as a statutory requirement. [13]

The Panel considers that tailings dam guidelines and criteria tailored to conditions in B.C. would more effectively meet the needs of the Province in protecting public safety. Those developed by the U.S. Army Corps of Engineers for water dams provide one example, among others, that might be used as a starting point. [12] This does not preclude adopting parts of the CDA Guidelines where appropriate as well as the CDA technical bulletin *Geotechnical Considerations for Dam Safety.* [14] The Panel anticipates that this will result in more prescriptive requirements for site investigation, failure mode recognition, selection of design properties, and specification of factors of safety.

Tailings dam guidelines and criteria tailored to conditions in B.C. would more effectively meet the needs of the Province in protecting public safety.

9 | Where Do We Go From Here?

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11) CDA, 2014, Technical Bulletin: Application of Dam Safety Guidelines to Mining Dams, Canadian Dam Association, 43 p.

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13) Health, Safety and Reclamation Code for Mines in British Columbia, 2008. Section 10.1.5, http://www.empr.gov.bc.ca/Mining/HealthandSafety/Pages/HSRC.aspx

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10 | Conclusions

Based on the activities described and interpretations advanced in the preceding sections of the report, the Panel has developed the findings summarized below.

10.1 MECHANISM OF FAILURE

The breach of the Perimeter Embankment on August 4, 2014 was caused by shear failure of dam foundation materials when the loading imposed by the dam exceeded the capacity of these materials to sustain it. The failure occurred rapidly and without precursors.

Direct evidence of this failure mechanism is provided by an identified shear surface in surviving remnants of the dam core and by deformations consistent with shearing in a weaker glacially-deposited layer of silt and clay about 8–10 metres (m) below the original ground surface. This layer, its properties, and its extent received intense scrutiny during this investigation, and analyses using representative parameters provide indirect evidence that further supports this failure mechanism.

Deposited in a complex geologic environment, the weaker glaciolacustrine layer was localized to the breach area. It went undetected, in part because the subsurface investigations were not tailored to the degree of this complexity. But neither was it ever targeted for investigation because the nature of its strength behaviour was not appreciated.

Throughout, the design investigations took note of the stiff, dense character of foundation soils and used corresponding strength properties in stability analyses. But it was not recognized that this character would change, with a corresponding change in strength behaviour under the increased loading as the dam grew higher. Specifically, it was never recognized that the glaciolacustrine soils that were initially overconsolidated would become normally consolidated, requiring undrained shear strengths for stability analyses. This is the process that affected the weaker glaciolacustrine layer in the breach area that was not accounted for in the design of the dam.

Adding to the antecedent foundation conditions was the unprecedented steepness of the 1.3H:1V Perimeter Embankment slope. This was justified by design analyses without questioning its reasonableness. The higher Main Embankment had glaciolacustrine foundation soils with properties broadly comparable to those at the breach section. But here, the steep slopes were effectively flattened by the addition of a buttress, which explains why the failure did not occur at the highest part of the dam.

10 | Conclusions

10.2 CONTRIBUTING FACTORS

10.2.1 LONG-TERM PLANNING

A lack of foresight in planning for dam raising contributed to the failure. Successfully executing the raising plan required intimate coordination of impoundment water-level projections, production and transport of mine waste for raising, and seasonal constraints on construction. This made the tailings dam contingent at the same time on the water balance, the Mine plan, and the weather. But instead of projecting these interactions into the future, they were evaluated a year at a time, with dam raising often bordering on ad hoc and only responding to events as they occurred. The effects were twofold: a near overtopping failure in May of 2014, and restrictions on mine waste availability that produced the oversteepened slopes and deferred buttress expansion.

10.2.2 OBSERVATIONAL METHOD

The Observational Method was adopted as a design philosophy, but misapplied. For reasons not unrelated to planning shortcomings, instrumentation was relied upon to substitute for definitive input parameters and design projections. But the Mount Polley dam was ill-suited to this approach, for both practical and strategic reasons. The steep slopes and constant construction activity on the Perimeter Embankment prevented installation of instruments at optimal locations. More importantly, the instrumentation program was incapable of detecting critical conditions because, once again, the critical materials and their critical mode of undrained behaviour were not recognized.

10 | Conclusions

10.3 ROLE OF WATER

In light of its importance in planning and the near-overtopping incident, the role of water contained in the tailings storage facility (TSF) deserves special mention. First of all, overtopping did not cause the breach of August 4, 2014. However, the high water level acted in other ways that influenced both the failure and its effects.

High impoundment water levels were a major cause of chronic problems in maintaining a tailings beach around the perimeter of the dam. At the breach section, water was in direct contact with the upstream zone of tailings fill when failure occurred. This increased the piezometric level in the upstream zone above what it would have been had a wide tailings beach been present. The Panel's analyses show that this had some influence on dam stability, although it was not the dominant factor.

The high water level was the final link in the chain of failure events. Immediately before the failure, the water was about 2.3 m below the dam core. The Panel's excavation of the failure surface showed that the crest dropped at least 3.3 m, which allowed overflow to begin and breaching to initiate. Had the water level been even a metre lower and the tailings beach commensurately wider, this last link might have held until dawn the next morning, allowing timely intervention and potentially turning a fatal condition into something survivable.

Finally, the quantity of water had a great deal to do with the quantity of tailings released after the breach developed. It was water erosion that transported the bulk of the tailings, and these fluvial processes ended when the supply of water was exhausted. Had there been less water to sustain them, the proportion of the tailings released from the TSF would have been less than the one-third that was actually lost.

10 | Conclusions

10.4 REGULATORY FACTORS

The Panel examined regulatory activities by the Ministry of Energy and Mines (MEM) in relation to the failure and whether different actions on MEM's part might have prevented it. In particular, the Panel's attention was drawn to the period from 2009 to 2011 when no government inspections of the Mount Polley dam were performed. The Panel concludes that this lack of inspection was immaterial to the failure because there were no precursors that could have been detected, even on the eve of the breach. By definition, no amount of inspection can discover a hidden flaw.

The Panel also examined MEM's actions concerning factors that did have a material relationship to the failure. In this regard, MEM queried the designer about softer conditions in glaciolacustrine soils encountered in a groundwater well that were similar to those at the breach. Its inspector issued a "Departure from Approval" notice concerning the absence of an adequate tailings beach. The inspector questioned the designer's factor of safety FS = 1.3 criterion, subsequently requiring its increase. The Panel found these actions to be appropriate and within the expected conduct of regulatory responsibilities.

It is not unreasonable to ask whether MEM could have acted sooner or more aggressively in these matters or even intervened in the design process, and perhaps this might have been warranted under the harsh illumination of hindsight. Yet the Panel considers that a bright line must be maintained between designer and Regulator. It is axiomatic that a Regulator cannot regulate its own activities. Were it to usurp the role of the designer, it would also usurp its own role.

10.5 POSSIBLE FAILURE PREVENTION

In fulfilling its Terms of Reference, the Panel considered what actions could have been taken to prevent the failure. From a purely technical perspective, apart from rectifying the deficiencies reviewed here, there is one that stands out.

The design for the next raise of the dam had been submitted only days before the failure. In it was a buttress that would have extended along the Perimeter Embankment, including the breach section. Although this buttress was still not designed using the appropriate stratigraphy or undrained strengths, the Panel determined that had it been in place, the failure would have been averted. The solution would have been correct, even if for the wrong reasons.

In keeping with its Terms of Reference, the Panel has developed these conclusions on the basis of technical factors specific to the Mount Polley failure. It must be left to others to determine how they might translate more broadly to legislative, administrative process, and policy areas.

11 | Recommendations

Recognizing that the path to zero failures involves a combination of best available technology (BAT) and best applicable practices (BAP), the Panel recommends the following:

1) To implement BAT using a phased approach:

a. **For existing tailings impoundments**. Rely on best practices for the remaining active life.

b. **For new tailings facilities**. BAT should be actively encouraged for new tailings facilities at existing and proposed mines.

c. **For closure**. BAT principles should be applied to closure of active impoundments so that they are progressively removed from the inventory by attrition.

See section 9.3.

2) To improve corporate governance:

Corporations proposing to operate a tailings storage facility (TSF) should be required to be a member of the Mining Association of Canada (MAC) or be obliged to commit to an equivalent program for tailings management, including the audit function.

See section 9.4.1.

3) To expand corporate design commitments:

Future permit applications for a new TSF should be based on a bankable feasibility that would have considered all technical, environmental, social and economic aspects of the project in sufficient detail to support an investment decision, which might have an accuracy of ±10%–15%. More explicitly, it should contain the following:

a. A detailed evaluation of all potential failure modes and a management scheme for all residual risk.

b. Detailed cost/benefit analyses of BAT tailings and closure options so that economic effects can be understood, recognizing that the results of the cost/benefit analyses should not supersede BAT safety considerations.

c. A detailed declaration of Quantitative Performance Objectives (QPOs).

See section 9.4.2.

11 | Recommendations

4) To enhance validation of safety and regulation of all phases of a TSF:

Increase utilization of Independent Tailings Review Boards.

See section 9.4.3.

5) To strengthen current regulatory operations:

a. Utilize the recent inspections of TSFs in the province to ascertain whether they may be at risk due to the following potential failure modes and take appropriate actions:

i. Undrained shear failure of silt and clay foundations

ii. Water balance adequacy

iii. Filter adequacy

b. Utilize the concept of QPOs to improve Regulator evaluation of ongoing facilities.

See section 9.4.4.

6) To improve professional practice:

Encourage the APEGBC to develop guidelines that would lead to improved site characterization for tailings dams with respect to the geological, geomorphological, hydrogeological and possibly seismotectonic characteristics.

See section 9.4.5.

7) To improve dam safety guidelines:

Recognizing the limitations of the current Canadian Dam Association (CDA) Guidelines incorporated as a statutory requirement, develop improved guidelines that are tailored to the conditions encountered with TSFs in British Columbia and that emphasize protecting public safety.

See section 9.4.6.

12 | Postscript and Acknowledgements

The Panel has been acutely aware of its responsibilities in conducting this investigation. It set out to be thorough, focusing on the technical issues, and to report its findings in an independent, open, transparent and timely manner. It is content that it has fulfilled its mandate. To do so required the digestion of thousands of pages of technical documents; field investigations involving mapping, drilling and sampling; complex laboratory tests; various theoretical analyses; and consolidation of its findings, conclusions and recommendations in a manner intended to be accessible to a variety of stakeholders. The Panel could not have met its objectives without the assistance of a number of dedicated and skilled individuals. The Panel wishes to acknowledge this assistance here.

First, and possibly foremost, the Panel expresses its gratitude to Mr. Kevin Richter, Assistant Deputy Minister, Ministry of Transportation and Infrastructure, who was appointed to lead the Secretariat for the investigation and his assistants, Stacy Scriver and Rupinder Prihar. Mr. Richter managed the business of the investigation with enormous skill, diplomacy and good grace. This allowed the Panel to focus on its main task and hence the Secretariat made a most valuable contribution to the collective effort.

The Panel retained Thurber Engineering Limited (Thurber) to undertake a wide variety of technical tasks acting under the direction of the Panel. These tasks involved site mapping, drilling and sampling, a wide suite of laboratory tests, a variety of analyses, and preparing material for inclusion in the report. The Thurber team was outstanding in its technical contributions and dedication to this assignment. The Panel was extremely pleased to work with such a skilled team that included the following:

- In Vancouver – David Regehr (Project Manager), Paul Wilson, Caleb Scott, Ben Singleton-Polster, Denny Ma, Andrea Lougheed, Paul Evans
- In Victoria – Stephen Bean, Warren Wunderlick, Suzanne Powell
- In Calgary – John Sobkowicz
- And others too numerous to mention

Deborah Lovett, QC, of Lovett & Westmacott was retained as legal advisor to the Panel and provided wise counsel throughout the period of the investigation.

Judith Brand provided senior editorial advice and Shawn Robins, Robins Communications, assisted the Panel in organizing its outreach activities.

While many have contributed to this report, the Panel retains sole responsibility for its content.

13 | List of Abbreviations

ABBREVIATIONS

APEGBC: Association of Professional Engineers and Geoscientists of British Columbia

BAP: best applicable practices

BAT: best available technology

CDA: Canadian Dam Association

CPT: cone penetration test

CQA: Construction Quality Assurance

DSR: Dam Safety Review

DSS: direct simple shear

EOR: Engineer of Record

EPRI: Electric Power Research Institute

ESA: effective-stress analysis

FOIPPA: *Freedom of Information and Protection of Privacy Act*

FS: factor of safety

GLU: Upper Glasciolacustrine Unit

GSA: grain size analyses

ITRB: Independent Tailings Review Board

KCB: Klohn Crippen Berger

KP: Knight Piésold

LiDAR: Light Detection And Ranging

LI: Liquidity Index

LPT: Large Penetration Testing

MAC: Mining Association of Canada

MEM: Ministry of Energy and Mines

MFLNRO: Ministry of Forests, Lands and Natural Resource Operations

MoE: Ministry of the Environment

MOU: Memorandum of Understanding

MPMC: Mount Polley Mining Corporation

OCR: overconsolidation ratio

OMS: Operations Maintenance and Surveillance

PMP: Probable Maximum Precipitation

QPO: Quantitative Performance Objective

RCPT: Resistivity Cone Penetration Test

S.O.L.: setting out line

SPT: standard penetration test

Thurber: Thurber Engineering Limited

TSF: tailings storage facility

TSM: Towards Sustainable Mining

USA: undrained strength analysis

USBR: U.S. Bureau of Reclamation

VST: vane shear test

14 | Glossary of Technical Terms

GLOSSARY

Angle of repose: the maximum slope steepness that dry granular material can sustain

Anisotropy: directional differences in properties, typically horizontal and vertical

Anticlinal structure: dome-shaped folding

Applied load: usually gravity stresses imposed by a structure; simplistically, its weight

Arcuate headscarps: semicircular and nearly perpendicular slopes delineating the upper end of a slope movement

Artesian pressure: water pressure sufficient to cause water to flow upwards out of the ground

Bankable feasibility study: a level of design sufficient for detailed cost estimates

Bathymetric survey: survey of underwater surfaces

Beach: a gently sloping surface of deposited tailings

Bedding: layering, commonly horizontal

Blow count: the number of drops of a heavy weight required to advance a sampler 30 cm into the ground

Buttress: a berm constructed at the bottom of a slope to increase its stability

Chimney drain: a zone of sand or gravel within a dam for collecting and conveying water

Coefficient of consolidation: a parameter used to calculate change of pore pressure with loading

Crest: the top of a dam or slope

Critical failure surface in stability analysis: the failure surface with the lowest factor of safety

Cycloning: separation of tailings into coarser and finer fractions

Dendritic drainages: branching stream channels

Dip direction: the direction in which a geologic structure slopes downward

Direct shear: type of test used to determine drained shear strength

Direct simple shear: type of test used to determine undrained shear strength

Downcutting: a natural process of excavation, usually by erosion

Downthrow: downward movement

Effective stress: the stress experienced by soil particles after the known pore pressure is subtracted

Effective-stress strength: the strength of a soil expressed only in terms of the effective stress

En echelon scarps: parallel steep slopes produced by ground movement

Factor of safety: the ratio of available strength to the strength required for equilibrium; a measure of stability

Fines: fine particles smaller than visible with the naked eye, typically less than 0.074 mm diameter

14 | Glossary of Technical Terms

Flowslide: high-velocity earth movement; mudflow

Fluvial processes: processes caused by or associated with rivers or streams

Freeboard: reservoir capacity reserved for storage of flood inflows, including wave height

Grab samples: disturbed samples

Graben: downdropped block within the ground

Headscarp: steep slope at the upper end of a landslide

Hydraulic-cell deposition: controlled discharge of tailings into a small, confined area

Hydraulic fracturing: cracking of soil caused by water pressure

Inclinometer: a device for measuring horizontal subsurface movements

Internal erosion: subsurface transport of soil particles by water

Interparticle voids: open spaces between soil particles

Glaciofluvial: associated with or deposited in a glacial stream

Glaciolacustrine: associated with or deposited in a glacial lake

Lift lines: boundaries between successive layers of compacted fill

Loading: the imposition of stresses or weight; see applied load

Marker bed: a prominent layer of soil or rock used as a reference

Normally consolidated: a state or condition of soil that is experiencing pressures equal to or exceeding the pressures that it has experienced in the past

Oedometer test: a test for measuring compression of soil under load

Offtake: a drain or pipe that discharges flow

Orthophoto imagery: aerial photograph looking directly down on the terrain

Overconsolidation: a state or condition of soil produced by past stresses greater than those that currently exist

Overtopping: water flowing over the crest of a retaining dam or structure

Phreatic surface: water table

Piezometer: a device for measuring subsurface water pressure

Piping: see internal erosion

Pore pressure: the pressure of water that exists within the voids of a soil mass; see interparticle voids

Preconsolidation pressure: the maximum pressure experienced by the soil in its past

Pre-shearing: the process or condition of having been previously sheared

Relic erosional surface: ground surface remaining after previous erosion

14 | Glossary of Technical Terms

Residual strength: strength of a soil after having been sheared; see also pre-shearing

Rills: small-scale gullies

Runup: the height of breaking waves on a slope

Sand tailings: coarser fraction of tailings

Scarp: a very steep, near-perpendicular slope at the head of a landslide; see also headscarp

Scour: erosion by surface water

Seepage flow: flow of subterranean water

Sentinel section: an instrumented section providing preliminary information; see also inclinometer, piezometer

Shear: a) the act or process of one surface sliding across another; b) a state of stress in the ground

Shell: a zone of material that supports the core of a dam

Slickenside: polished surface resulting from shearing

Slimes: finer fraction of tailings

Slump blocks: large masses subject to or transported by downslope movement

Stereopairs: aerial photographs producing a three-dimensional image

Stratigraphy: systematic or characteristic layering exhibited by soil or rock at a particular locale

Substrate: underlying soil

Survey monuments: fixed reference points for measuring relative movements

Tailings: finely ground rock particles remaining after extraction of valuable minerals

Tailings beach: see beach

Till: unsorted glacial sediment moved or deposited directly by the glacier

Tip resistance: the pressure measured at the tip of the cone during CPT testing

Toe: bottom of a slope

Triaxial test: type of test used here to determine drained and undrained strength

Undrained strength: the strength of a soil that incorporates the effect of pore pressures generated by shearing

Undrained strength ratio: the ratio of undrained strength to effective stress

Vane testing: an in situ test for measuring undrained strength of clays

Varving: thinly laminated layering

Water balance: an accounting of water inputs and outputs for determining water accumulation or deficit

Whaleback: a linear bulge or uplift

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"Technical Support for Grassroots Public Interest Groups"

April 30, 2015

To: Betsy Daub
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Re: Comments on the Geotechnical Stability of the Proposed NorthMet Tailings Basin and Hydrometallurgical Residue Facility in light of the Failure of the Mt Polley Tailings Storage Facility.

On March 14, 2014, the Center for Science in Public Participation (CSP2) submitted comments on the Supplemental Draft Environmental Impact Statement to Lisa Fay, EIS Project Manager, MDNR Division of Ecological and Water Resources, Environmental Review Unit, that included comments on EIS section 5.2.14 Geotechnical Stability, subsections 5.2.14.2.2 Tailings Basin, and 5.2.14.2.3 Hydrometallurgical Residue Facility.

The failure of the Mt Polley Tailings Storage Facility (TSF) has bearing on several features of the proposed NorthMet TSF and Hydrometallurgical Residue Facility. In this report CSP2 will augment its comments of March 14, 2014, to include reflections of the factors involved in the Mt Polley TSF failure that might also come into play at NorthMet.

Also included in this report as Appendix 1 is "A Review of the Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel."[1]

Sincerely;

David M Chamber, Ph.D., P. Geop.

[1] The original report is: "Report on Mount Polley 2015. Dr. Norbert R. Morgenstern (Chair), CM, AOE, FRSC, FCAE, Ph.D., P.Eng.; Mr. Steven G. Vick, M.Sc., P.E.; and, Dr. Dirk Van Zyl, Ph.D., P.E., P.Eng. Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel, Province of British Columbia, January 30, 2015"

EXECUTIVE SUMMARY

One of the driving conclusions of the Expert Panel on the Mt Polley tailings dam failure is that the Panel "… *firmly rejects any notion that business as usual can continue*." *(Report on Mount Polley 2015, p. 118)*

They went on to recommend:

> *"For new tailings facilities – BAT* (Best Available Technologies) *should be actively encouraged for new tailings facilities at existing and proposed mines. Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor." (Report on Mount Polley 2015, p. 125)*

If taken at face value, as they should be, the recommendations of the Expert Panel clearly say there is a crisis occurring with tailings dam construction and management today. This can also be seen in comparing failure rates of tailings dam to that of conventional water supply reservoir dams – tailings dams fail at rate that is approximately ten times higher than that of water supply reservoir dams (Davies, M.P., 2002, p. 32). There is no engineering reason for this phenomenon to take place, and it is probably the prime indicator that something is wrong with the way tailings dams are designed, constructed, and/or operated.

The primary implications of catastrophic tailings dam failures are:

- public safety (fatalities that result from dam failures);
- economic losses (loss of revenue from business impacted by the accident, as well as the cost of cleanup which is typically borne by public/taxpayer); and
- environmental degradation (even if the tailings released can be cleaned up, complete recovery is impossible and some level of long-term environmental degradation results).

The implications of the recommendations from the Mt Polley Expert Panel should have a direct impact on at least two aspects of the proposed NorthMet Tailings Basin.

First, regulators should reconsider use of old taconite tailings basins/dams for the addition of the non-acid generating NorthMet rougher tailings. The existing taconite tailings basin was constructed using the upstream-type dam construction method. Upstream-type dam construction is statistically the least safe of the three methods of tailings dam construction, and NorthMet will not only be using this same type of dam construction for its future dam expansion, but will also need to depend in part on the safety of the design and construction of the old NorthMet dams, and the underlying geology and nature of the taconite tailings for support of the tailings dam extensions. Neither the existing tailings dam facilities, nor the expansions designed by NorthMet, are designed to be "dry closure" facilities as recommended by Mt Polley Expert Panel. Extending a risky design on top of an old design that itself poses higher risk, against the recommendation of the Mt Polley Expert Panel for dry closure, for a facility that has not yet received regulatory approval, would not be recognizing the long-term risks being posed to the public.

Second, regulators should reconsider whether to construct a wet tailings basin to hold the acid-generating NorthMet tailings. The design of the Hydrometallurgical Residue Facility would also be contrary to the dry closure recommendation of the Mt Polley Expert Panel. In this instance the Panel's recommendation would probably be best met by a dry stack closure design for the Hydrometallurgical Residue Facility. Again, since the mine proposal is still in the draft stage, the design of the Hydrometallurgical Residue Facility should be reconsidered in light of the Mt Polley Expert Panel recommendations.

<u>COMMENTS ON SDEIS SECTIONS</u>

SDEIS Comments from 14Mar14:

5.2.14 Geotechnical Stability

5.2.14.2.2 Tailings Basin

In discussing the construction of the new tailings facility, it is noted:

> *"The Tailings Basin would be constructed using the upstream method, whereby NorthMet dam embankments would be constructed using preferentially borrowed LTVSMC tailings on top of the existing LTVSMC tailings embankment and on the spigotted tailings adjacent to the perimeter embankment." (SDEIS, p 5-561)*

Upstream construction poses the highest risk for seismic and static failure of tailings dams. Most tailings dam failures have been associated with upstream dam construction.

A significant concern with upstream tailings dam construction is its susceptibility to failure during earthquakes. If the tailings upon which the dam is constructed are saturated with water, the tailings do not form a stable foundation for the dam under seismic loading.

Tailings are placed in a saturated state. Tailings materials are relatively uniform in their size and shape, and typically have very low permeability, a fact often cited by mining engineers to argue that liners are not needed for tailings facilities. As a result, it will be difficult to consistently drain the water from all the tailings under the proposed dam expansion.

Continuing to use upstream-type dam construction methods to increase the capacity of the tailings at the NorthMet tailings facility is the least expensive dam construction approach, but poses the most risk to long term seismic stability.

PolyMet picked a "critical" cross section, noting:

"Geotechnical conditions along the length of existing LTVSMC Tailings Basin dams have varying layers of coarse, fine, and slime tailings. Cross Section F, which intersects the northern dam of Cell 2E, as shown in Figure 5.2.14-4, was selected to represent the critical cross section for stability analysis purposes as it is the maximum section and some layers of the weaker fine and slime tailings extend close to the dam embankment, and the dam embankment is underlain by peat." (SDEIS, p 5-565)

(see Figure 5.2.14-5: Cross Section F of the Tailings Basin at Maximum Extent)

The dark blue segment in Figure 5.2.14-5 is the existing tailings dam, and the lighter blue would be the new upstream raises. This figure illustrates very well the importance of the stability of the tailings as a base for the upstream dam.

Mt Polley Implications:

Failure to detect a clays layer beneath the portion of the dam that failed is the primary cause of the Mt Polley accident. This type of failure can occur even absent seismic activity, as the Mt. Polley accident demonstrates. As can be seen from Figure 2 the upstream-type dams will be built on "LTVSMC tailings slimes." These slimes are of a consistency and similar behavior to clays. One of main issues here is be the variability in the consistency of the slimes beneath the upstream tailings dams.

The drill holes bored for the Mt Polley dam foundation sampling were either not spaced close enough, or deep enough, to detect the clay layer that caused the dam to fail. If detected, both the physical properties and thickness of the material in question become significant for predicting how the dam will behave under both static and seismic loading. At Mt Polley the dam designers knew there were clay layers associated with old glacial lakes in the area. The one they knew about was deeper than the one they didn't know about, and deeper glacial lake clays response to the increased pressures from the weight of both the tailings dam and tailings/water themselves was better than that of the shallower (~ 8-10 meters) glacial lake clay they didn't detect.

Many dam-response models assume that the physical properties of each vertical layer are uniform. In fact these properties probably vary in three dimensions. This is one reason why full dynamic modeling should be required for all large tailings dams (like NorthMet), instead of pseudo-static modeling. But even full dynamic modeling is not able to account for all of the complexities of the real geology.

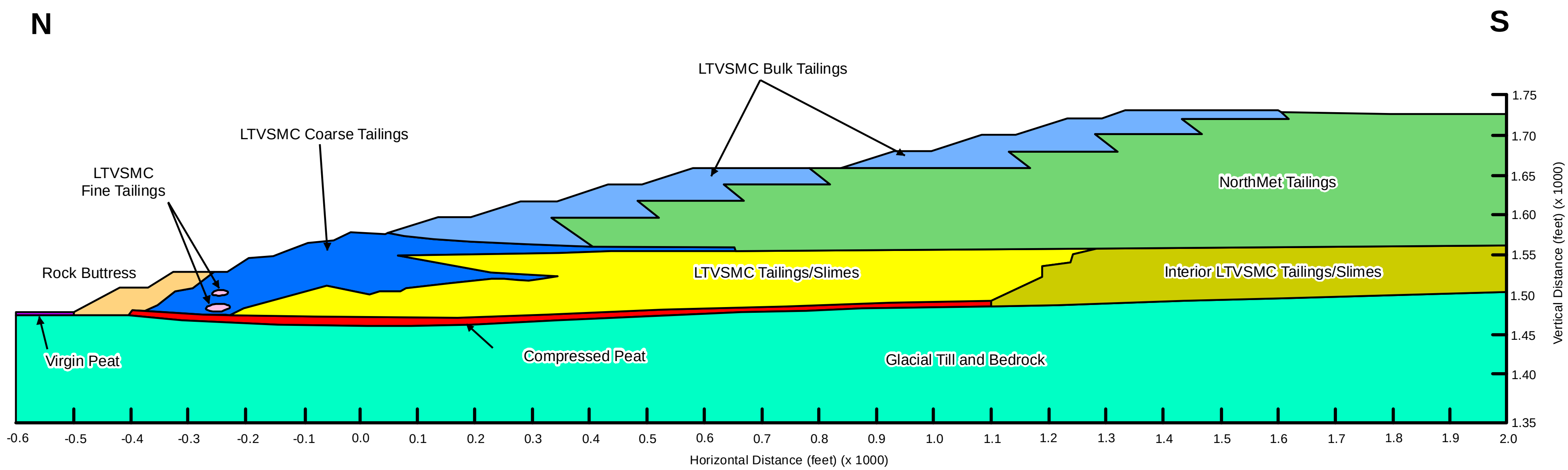
The construction of a new tailings disposal facility on top of an existing tailings facility with problematic features, namely existing upstream construction and slimes as a foundation material, encompasses two of the factors that led to the Mt Polley TSF failure.

As noted above upstream dam construction is the least stable dam construction type. In its recommendations, the Mt Polley Review Panel clearly recommends:

- *For existing tailings impoundments. Constructing filtered tailings facilities on existing conventional impoundments poses several technical hurdles. Chief among them is undrained shear failure in the underlying saturated tailings, similar to what caused the Mount Polley incident. Attempting to retrofit existing conventional tailings impoundments is therefore not recommended, with reliance instead on best practices during their remaining active life.*
- *For new tailings facilities. BAT* (Best Available Technology) *should be actively encouraged for new tailings facilities at existing and proposed mines. Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor.*
- *For closure. BAT principles should be applied to closure of active impoundments so that they are progressively removed from the inventory by attrition. Where applicable, alternatives to water covers should be aggressively pursued. (Report on Mount Polley 2015, p. 125)*

In its recommendations for existing tailings impoundments the Panel is warning that "*Chief among them* (technical hurdles) *is undrained shear failure in the underlying saturated tailings…*" Undrained shear strength of the slimes under the proposed upstream tailings impoundment expansion is an issue, given the revelations of the Panel about the frequency of the drillholes. Coupled with the lack of associated lab work for the drillholes at Mt Polley, it is not clear that these issues are adequately addressed at NorthMet (Existing drillholes for NorthMet are plotted on Figure B-1, Historic and Current Geotechnical Test Locations – Barr Engineering 22Sep11). An independent review panel, as recommended by the Panel Report for Mt Polley, should be convened to review the adequacy of the long term storage design for NorthMet.

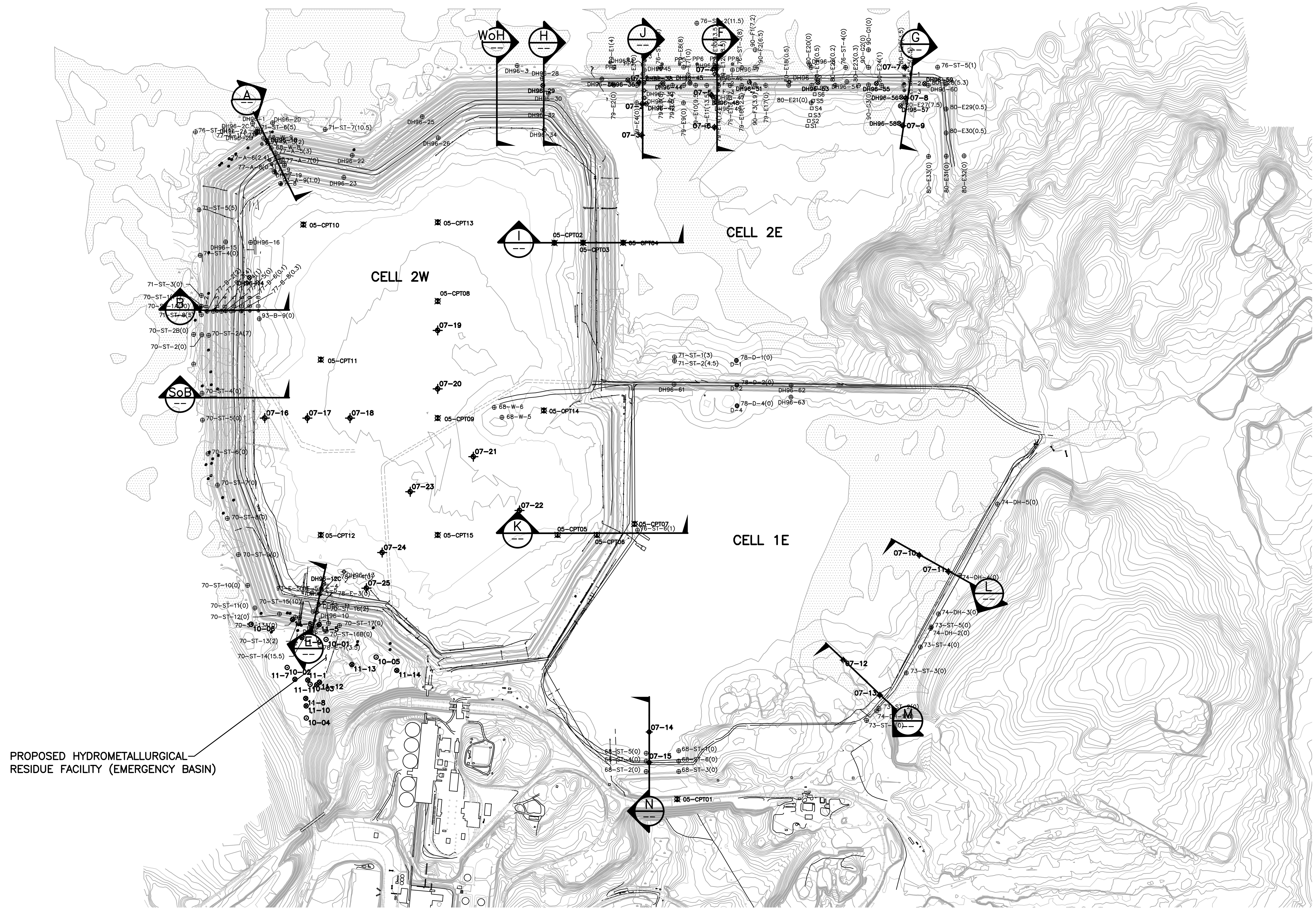
For new TSFs, the recommended direction of the Independent Expert Engineering Investigation and Review Panel is clear – dry tailings, underground tailings disposal, or other non-wet alternatives. Reason would say that since "*… cost should not be the determining factor" (Report on Mount Polley 2015, p. 125)* all new impoundments should be dry, but economics is still the strongest driving factor in any mine proposal.



Compressed Peat	LTVSMC Tailings/Slimes
Interior LTVSMC Tailings/Slimes	LTVSMC Fine Tailings
NorthMet Tailings	Rock Buttress
LTVSMC Bulk Tailings	Virgin Peat
LTVSMC Coarse Tailings	Glacial Till and Bedrock

Figure 5.2.14-5
Cross Section F of the Tailings Basin at Maximum Extent
NorthMet Mining Project and Land Exchange SDEIS
Minnesota

November 2013



0 1000 2000
SCALE IN FEET

LEGEND:

- 07–1 BARR 2007 INVESTIGATION LOCATIONS (PROPOSED)
- 10–04 BARR 2010 INVESTIGATION LOCATIONS (PROPOSED)
- 11–10 BARR 2011 INVESTIGATION LOCATIONS (PROPOSED)
- SWAMP/PEAT AREAS

NOTE:

ELEVATIONS AND DIGITIZED LINES PROVIDED BY MARKHURD ENGINEERING BASED ON PHOTOS TAKEN MAY, 1994.

PRELIMINARY DRAFT 09/22/11

NO.	BY	CHK.	APP.	DATE	REVISION DESCRIPTION

I HEREBY CERTIFY THAT THIS PLAN, SPECIFICATION, OR REPORT WAS PREPARED BY ME OR UNDER MY DIRECT SUPERVISION AND THAT I AM A DULY LICENSED PROFESSIONAL ENGINEER UNDER THE LAWS OF THE STATE OF MINNESOTA.

SIGNATURE ______

PRINTED NAME ______

DATE ______ REG. NO. ______

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BARR

Corporate Headquarters: Minneapolis, Minnesota Ph: 1–800–632–2277

Project Office: BARR ENGINEERING CO. 4700 WEST 77TH STREET MINNEAPOLIS, MN. 55435–4803 Ph: 1–800–632–2277 Fax: (952) 832–2601 www.barr.com

Scale	AS SHOWN
Date	08/11/2011
Drawn	DMD
Checked	EJB
Designed	EJB
Approved	

POLYMET MINING CORPORATION
HOYT LAKES, MINNESOTA

NORTHMET MINE AND ORE PROCESSING FACILITY

HISTORICAL AND CURRENT GEOTECHNICAL TEST LOCATIONS

BARR PROJECT No. 23690862.00
CLIENT PROJECT No.
DWG. No. Fig B-1
REV. No.

The Panel also observed: "*The Panel firmly rejects any notion that business as usual can continue*." *(Report on Mount Polley 2015, p. 118)* The Panel is saying safety, not cost, should be the determining factor in waste impoundment design. The use of the existing tailings pond, and the choice of upstream-type dam construction, are clearly driven by economic considerations.

Before Mt Polley, the engineering companies and the regulatory agencies regularly took the position that a Mt Polley-type failure— the failure of a dam designed and monitored by a reputable engineering company, regulated by an agency in an economically-developed country—could not happen. Not that it was not likely to happen, but that it could not happen. But it did. That was the surprise at Mt Polley, that the system of engineering design and oversight was not robust enough to detect that failure before it happened. This is why the Independent Expert Engineering Investigation and Review Panel "*… firmly rejects any notion that business as usual can continue*."

Returning to the SDEIS Comments from 14Mar14:

It is then noted in the SDEIS:

> *"The results reported in Geotechnical Data Package Volume 1 Version 4 indicate that the proposed design of the Tailings Basin would meet all respective Factors of Safety as required (PolyMet 2013n)." (SDEIS, p 5-565)*

There are several problems with the otherwise good work in Geotechnical Data Package Volume 1 Version 4:

1) The Probabilistic Seismic Hazard Analysis (PSHA) considers the 2,475-year return seismic event to be the largest earthquake the dam will experience. The PSHA should have used the Maximum Credible Earthquake (MCE) as the design earthquake.

   The design earthquake should represent the ground motions or fault movements from the most severe earthquake considered at the site. Since a tailings dam must stand in perpetuity, the design earthquake should be equivalent to the Maximum Credible Earthquake.

   The estimated largest earthquake that could occur at any given location is called the Maximum Credible Earthquake. The MCE is defined as the greatest earthquake that reasonably could be generated by a specific seismic source, based on seismological and geologic evidence and interpretations. The Maximum Credible Earthquake is most often associated with a recurrence interval of 10,000 years.[2]

   If the MCE/10,000-year event is used for the analysis of the 2,475-year event, the horizontal acceleration (horizontal g-force the dam is subject to) will increase significantly.

2) The mean distance to the nearfield earthquake is 100 miles. Probabilistic determination for the size of the largest earthquake is appropriate, but the assumption of 100 miles for nearfield is going to make the horizontal acceleration used to design the dam lower than what it should be.

   The further away the tailings dam is from the location of the earthquake, the less energy the tailings dam will need to withstand in order to maintain its structural integrity. The closer the location of the earthquake to the tailings dam, the higher the cost of building the dam, because the closer the earthquake the more energy the dam will have to withstand.

   Seismologists know that there are many active faults that have not been mapped or have been mapped inaccurately, that some faults believed to be inactive may actually be active, and that there are many inactive faults that may become active again. Because of these considerations, probabilistic methods

[2] Large Dams the First Structures Designed Systematically Against Earthquakes, Martin Wieland, ICOLD, The 14th World Conference on Earthquake Engineering, Beijing, China, October 12-17, 2008

are the more conservative way to determine the magnitude of a Maximum Credible Earthquake for dam analysis.

For tailings dams the most conservative choice for the location of the Maximum Credible Earthquake would be what is sometimes referred to as a ‘floating earthquake’ on an undiscovered fault that passes very near the site of the dam. This is a way of recognizing that we do not know the present, future, and even the past locations of significant faulting, and associated earthquakes.[3] The conservative choice for a Maximum Design Earthquake would be a Maximum Credible Earthquake that ruptures the ground surface on which the dam is built.

3) The evaluation for dam stability does not employ dynamic modeling.

Polymet did not perform dynamic modeling for the tailings dams.

“Results of the seismic liquefaction screening evaluation (Section 6.5.3.3) indicate that seismic triggering will not occur. As the ***seismic design event (2,475-year return period)*** *would not trigger liquefaction in any FTB materials, per the Work Plan (Attachment A),* ***no additional seismic triggering analyses were necessary****.” (Geotechnical Data Package Volume 1 – Flotation Tailings Basin Version 4, PolyMet Mining, April 12, 2013, p 92,* ***emphasis added****)*

PolyMet performed what might be termed a pseudostatic analysis. Today, most US regulatory agencies will not accept pseudostatic methods for seismic design of new dam projects. Dynamic analysis of seismic loading for most new dams is required if the maximum credible earthquake produces a peak ground acceleration of more than 0.1 g at the site.[4]

A pseudostatic analysis (sometimes called seismic coefficient analysis) should only be considered as an index of the seismic resistance available in a structure not subject to build-up of pore pressure from shaking. It is not possible to predict failure by pseudostatic analysis, and other types of analysis are generally required to provide a more reliable basis for evaluating field performance.[5]

An example of a government agency which happens to focus on dam safety and that will not accept pseudostatic analysis is the Federal Energy Management Agency (FEMA). FEMA practice previously allowed the use of the pseudostatic method of analysis in areas of low or negligible seismicity. FEMA does not recommend the pseudostatic analysis to judge the seismic stability of embankment dams.[6]

Dynamic analysis is the most rigorous method of evaluating dam survivability under seismic loading. Typically a dynamic analysis will use finite element or finite difference programs such as TARA (Finn et al 1986), FLAC (Itasca Group 2002), or PLAXIS (PlaxisBV 2002) in which dynamic response, pore-pressure development, and deformations can be fully coupled.[7]

These tailings dams must contain this material in perpetuity. If not, the cost of collecting spillage due to an earthquake-related failure, and rebuilding the containment structure, would be many millions of today’s dollars. This is not a risk, or cost, that should be passed on to future generations. If these

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[3] Safety of Dams, Flood and Earthquake Criteria, Committee on Safety Criteria for Dams, Water Science and Technology Board, Commission on Engineering and Technical Systems, National Research Council, National Academies Press, Washington, D. C. 1985
[4] http://www.meadhunt.com/documents/newsletters/persp_water3.pdf, downloaded on 14Jan10
[5] Federal Guidelines for Dam Safety Earthquake Analyses and Design of Dams, Federal Energy Management Agency, May 2005, p. 35
[6] Federal Guidelines for Dam Safety Earthquake Analyses and Design of Dams, Federal Energy Management Agency, May 2005, p. 38
[7] See Federal Guidelines for Dam Safety Earthquake Analyses and Design of Dams, Federal Energy Management Agency, May 2005, p. 32

containment structures are going to be built, the assumptions used to check the design should be conservative, and the models the best available.

Mt Polley Implications:

If there had been an earthquake at Mt Polley, it would likely have triggered a failure as well. But the dam failure at Mt Polley is what is called a static failure – the dam failed under its own weight. In addition to the failure to detect the glacial lake (clay layer) under the dam, there was another significant contributing factor – the dam was not being constructed according to its original design.

The plans for the dam originally called for a downstream slope of 2.0 horizontal to 1.0 vertical. Early on in the construction of the dam, which at the time of the failure had occurred in nine separately approved construction events, a decision had been made to build the dam at a steeper slope (1.3 horizontal to 1.0 vertical) until enough construction rock became available to fill in the downstream "buttress" of the dam. The result was that that the steeper-sloped dam put more pressure on a smaller area, causing it to fail. As noted by the panel, if the dam had been constructed as designed, with a downstream slope of 2.0 horizontal to 1.0 vertical, the pressure from the dam and tailings would have been distributed over a greater area, and the dam would not have failed (Report on Mount Polley 2015, p.108).

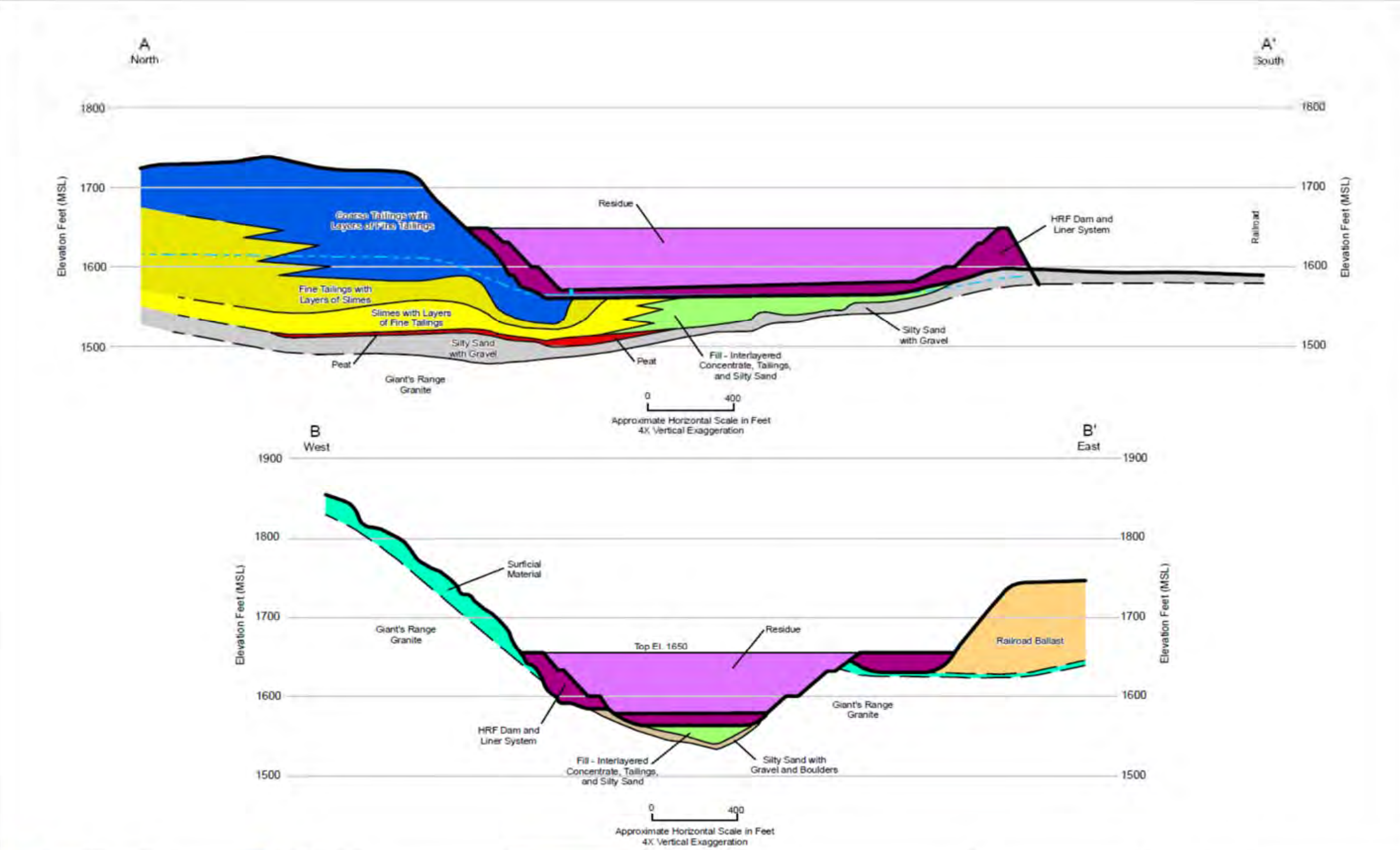
While this is a significant contributing factor, the basic cause of the dam failure (failure to detect the glacial lake sediments) remains the same. It is unlikely that a lack of construction material would lead to a similar problem at NorthMet, since the dam proposed would be constructed of existing tailings.

However, another factor that was being used at Mt Polley, which could come into play at NorthMet is also of concern – use of the "Observational Method" for dam construction. The Mt. Polley Panel noted that the Observational Method is a "*commonly accepted approach*" (Report on Mount Polley 2015, p.77) in managing dams. A more candid observation is the Observational Method is another way of saying there will be deviations from the original plan for construction/operation. The Observational Method was invoked for the Mt Polley tailings dam because sufficient quantities of waste rock were not available to build the downstream slope (buttress) of the dam out at a 2H:1V slope as called for in the original dam plans. Instead the downstream slope was built at a steeper 1.3H:1V. The dam designers thought this would be safe, but they didn't know about the glacial lake clays. Had they know about the glacial lake clays, they would have known that building the dam this steep, even temporarily, was not safe. Ironically, if they had built the dam to its original 2H:1V specification, even with the undetected glacial lake clays the dam would have held.

The tailings pond was also being operated with much more water in it than had been planned, again under the auspices of the Observational Method.

Managing mine water was an issue because the water balance predictions were not accurate. The water balance model included the site-specific information to the date of analysis, and future conditions were based on average climatic conditions. They did not account for specific wet year conditions. This is an issue that should have been apparent to both regulators and mine designers, but was either missed or ignored.

The mine had received permission to discharge treated water to resolve this problem, and a treatment plant was scheduled to begin operation in September, 2014. The accident happened on August 4, 2014. Earlier in 2014 the tailings pond faced a potentially catastrophic situation when water reached the top of the dam, and began to overflow. If this had continued, it too would have caused a catastrophic dam failure with concurrent release of tailings and contaminated water, much like the August accident.



Coarse Tailings with Layers of Fine Tailings
Fill - Interlayered Concentrate, Tailings, and Silty Sand
Fine Tailings with Layers of Slimes
Slimes with Layers of Fine Tailings
Peat
Railroad Ballast
Residue
Silty Sand with Gravel
Silty Sand with Gravel and Boulders
HRF Dam and Liner System
Surficial Material

US Army Corps of Engineers
St. Paul District

Figure 5.2.14-6
Cross Sections A and B of the
Hydrometallurgical Residue Facility at Year 20
NorthMet Mining Project and Land Exchange SDEIS
Minnesota

November 2013

The overflow of water due to the high water level in the tailings pond caused the mass release of tailings and contaminated water. There would have been a dam breach at Mt Polley even absent the water, but with no water there would have been little tailings release. There would probably have been minimal or no tailings release if the tailings pond were at normal levels – but it wasn't, and the tailings pond full of water led to the large release of tailings downstream.

In the view of the Panel, the Operational Method was misapplied at Mt Polley (Report on Mount Polley 2015, p.136). But more succinctly, the Operational Method was probably invoked at Mt Polley in order to keep mine operation on schedule. Invoking the Operational Method eventually led to the dam failure.

There appears to be no regulatory guidelines as to when the Operational Method can be invoked, or what should be done to put a dam operated under the Operational Method back on its planned track. This is a concern that is appropriate for consideration at NorthMet.

Returning to the EIS Comments from 14Mar14:

5.2.14 Geotechnical Stability

5.2.14.2.3 Hydrometallurgical Residue Facility

Global Slope Stability

As described above with the tailings basin geotechnical design, similarly there was no dynamic modeling for the hydrometallurgical facility.

> *"Liquefaction analysis was not applicable and not performed because the material proposed in the constructed dams would be well-compacted and the Hydrometallurgical Residue Facility liner system would limit leakage through the dams." (SDEIS, p 5-575)*

Even though the construction of the hydrometallurgical facility dam is downstream, the safest type of dam construction, the material that this facility holds is potentially very dangerous to both human health and the environment – if it were to be released. As a result, the geotechnical analysis of the dam should be conservative, and as with the bulk tailings dam, dynamic modeling should be performed.

In addition, it is proposed that the hydrometallurgical facility be placed on a residual layer of taconite tailings.

According to SDEIS Figure 5.2. 14-6 above a large portion of the hydrometallurgical facility (and liner system) will lie on: "Coarse Tailings with Layers of Fine Tailings, Fine Tailings with Layers of Slimes; Slimes with Layers of Fine Tailings; Fill – Interlayered Concentrate, Tailings, and Silty Sand; Silty Sand with Gravel; and, Peat."

Even if this material will be "well-compacted" it would be safer to remove the original peat and silty sand/gravel, and the taconite tailings and slimes, and replacing this material with compacted fill, so that the hydrometallurgical facility is built on a well prepared and verifiably stable base. This is the conservative approach.

Recommendation: The underlying original ground and the taconite waste should be removed from underneath the hydrometallurgical tailings facility, an engineered stable base installed, and dynamic modeling performed on the hydrometallurgical dam.

Mt. Polley Implications:

As noted above, even though downstream-type construction will be used for the hydrometallurgical facility dam, it would be built on a thick layer of taconite tailings. And a large portion of the hydrometallurgical facility (and liner system) will lie on: "Coarse Tailings with Layers of Fine Tailings, Fine Tailings with Layers of Slimes; Slimes with Layers of Fine Tailings; Fill – Interlayered Concentrate, Tailings, and Silty Sand; Silty Sand with Gravel; and, Peat."

According to the presentation on SDEIS Figure 5.2. 14-6, this material is over 50 feet deep under the north embankment of the hydrometallurgical facility. It is not practical to mechanically compact this material without removing and reapplying it, so the statement that it is "well-compacted" (see quote in Global Slope Stability above) will depend on its in situ conditions.

In short, the recommendation of the Panel, that a waste facility should be "…*independent of the integrity of any containment structures" (Report on Mount Polley 2015, p.121)* should be seriously investigated.

The Panel did not make this recommendation lightly. It also acknowledged *"The Panel recognizes that creating dry tailings may increase the amount of water requiring treatment or storage." (Report on Mount Polley 2015, p.122)*

References Supplied as a part of these Comments:[8]

Davies, M.P., 2002, "Tailings Impoundment Failures: Are Geotechnical Engineers Listening?" Michael P. Davies, Geotechnical News, September 2002, pp. 31-36.

Federal Guidelines for Dam Safety, Earthquake Analyses and Design of Dams, Federal Emergency Management Agency, May 2005

Large Dams the First Structures Designed Systematically Against Earthquakes, Martin Wieland, ICOLD, The 14th World Conference on Earthquake Engineering, Beijing, China, October 12-17, 2008

PolyMet 2013e, NorthMet Project Water Management Plan – Mine, Version 2. January 9, 2013

PolyMet 2013n, NorthMet Project Geotechnical Data Package - Flotation Tailings Basin, Volume 1, Version 4. April 12, 2013.

Report on Mount Polley 2015. Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel, Dr. Norbert R. Morgenstern (Chair), CM, AOE, FRSC, FCAE, Ph.D., P.Eng.; Mr. Steven G. Vick, M.Sc., P.E.; and, Dr. Dirk Van Zyl, Ph.D., P.E., P.Eng.; Province of British Columbia, January 30, 2015

Safety of Dams, Flood and Earthquake Criteria, Committee on Safety Criteria for Dams, Water Science and Technology Board, Commission on Engineering and Technical Systems, National Research Council, National Academies Press, Washington, D. C. 1985 (294 pages, available for reading but not copying online at http://www.nap.edu/catalog.php?record_id=288)

[8] The PolyMet references are not provided because they are references from the SDEIS. One reference, a book, Safety of Dams, Flood and Earthquake Criteria, is available online for reading but not copying.

Appendix 1

A Review of the

Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel

David M Chambers
Center for Science in Public Participation
February, 2015

A Review of the Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel

David M Chambers
Center for Science in Public Participation
February, 2015

Early on August 4, 2014, the Perimeter Embankment at the Mt Polley copper mine near Likely, south-central British Columbia, failed catastrophically. The loss of containment was sudden, with no warning. That failure, which released at least 25 million cubic meters of mine tailings and mine effluent mixed with stormwater into Polley Lake, Hazeltine Creek and finally stopped when it reached Quesnel Lake, a large salmon-spawning fjord-type lake.

The Cariboo Regional District declared a local state of emergency in several nearby communities, the Interior Health Authority ordered drinking water bans, and the Department of Fisheries and Oceans closed the recreational salmon fishery on the Quesnel and Cariboo Rivers. Fortunately, there were no human fatalities or injuries.

Why did the Mt Polley TSF Fail?

The failure of the Mt Polley Tailings Storage Facility (TSF) was reviewed shortly after the accident by an expert panel of three engineers.[1] The words of the panel itself succinctly describes what happened, why it happened, and what we should be doing to avoid similar TSF failures in the future.

> *The Panel concluded that the dominant contribution to the failure resides in the design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. As a result, foundation investigations and associated site characterization failed to identify a continuous GLU (Glasciolacustrine Unit) layer in the vicinity of the breach and to recognize that it was susceptible to undrained failure when subject to the stresses associated with the embankment.*

The tailings dam was built on top of an old, relatively small, glacial lake that contained mainly clays. The builders of the dam, Knight-Piesold Ltd., made several assumptions that led to this problem. They assumed that the extent of the clay was less widespread that it in fact was, and that the clay constituting the lake sediment (called the Upper Glasciolacustrine Unit – GLU) would not loose shear strength as the sediment was loaded by the weight of the dam, tailings, and water. These proved to be both flawed and ultimately fatal assumptions for the dam.

Figure 1 (from the Report) maps the resulting failure on top of an aerial photo of the failed dam. The increasing load due to the ongoing construction of the dam, and the load of tailings and water behind the dam, finally caused the glacial clay lake-layer to break and slide, rupturing the dam. There were no precursor warnings to the failure. The failed piece of the dam rotated down and out, letting water spill over the top of the failed segment, and in a short time washed that piece of dam away, carrying in its wake almost the entire contents of the tailings basin.

[1]Dr. Norbert R. Morgenstern (Chair), CM, AOE, FRSC, FCAE, Ph.D., P.Eng.; Mr. Steven G. Vick, M.Sc., P.E.; and, Dr. Dirk Van Zyl, Ph.D., P.E., P.Eng. Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel, Province of British Columbia, January 30, 2015

Figure 1: Plan Showing Direction and Extent of Mass Movements

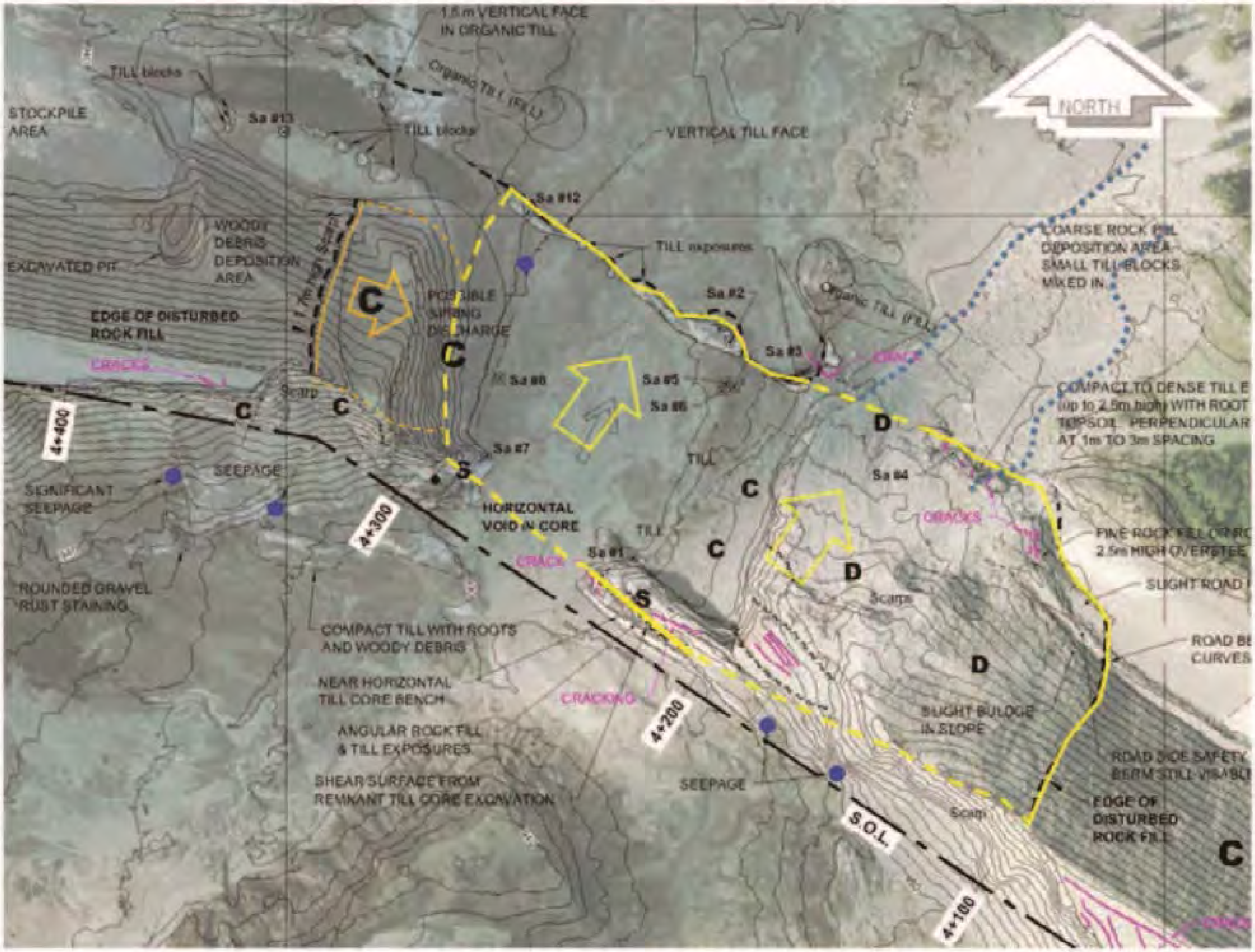
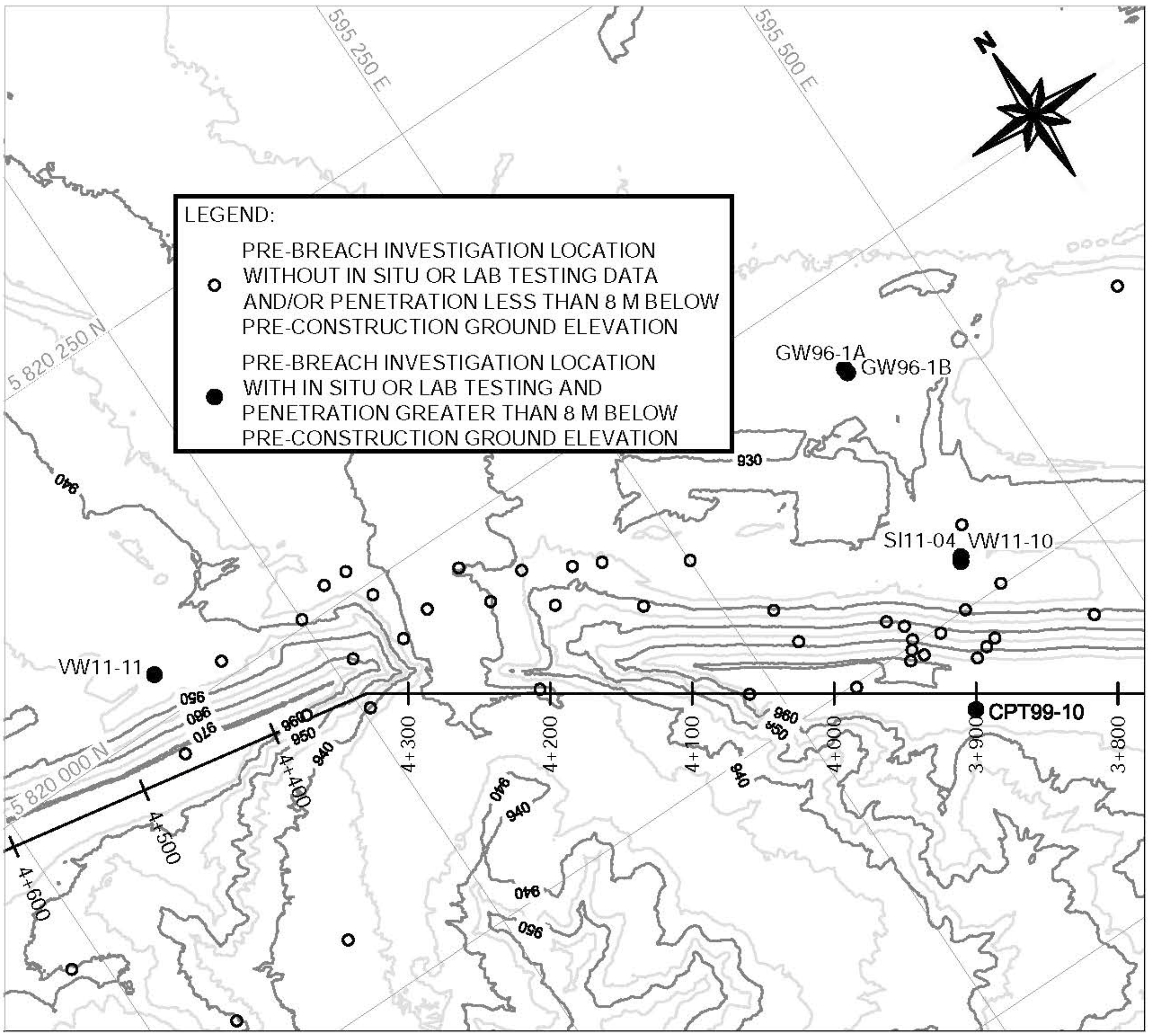


Figure 2 shows the drillholes made before the dam was built. The pre-failure drillholes, depicted as solid circles in Figure 2, were drilled deep enough to intersect the Upper Glasciolacustrine Unit, and clays intersected in those holes were lab tested for shear strength. The pre-failure drillholes depicted as open circles were not drilled deep enough to intersect the Upper GLU.

As can be seen in Figure 2, there are only shallow drillholes (open circles) in the area of the failed dam segment. There are no drillholes in the area of the dam failure that intersected the Upper GLU or that were lab tested for shear strength.

Figure 2: Pre-Failure Site Investigation Drillhole Locations in Breach Area



Post-failure drilling in the area of the failure, Figure 3, did intersect the Upper GLU, and lab testing of these clays clearly determined that the clay of the Upper GLU would fail under the increased pressures of the dam and tailings.

Figure 3: Joint and Panel Site Investigation Drillhole Locations

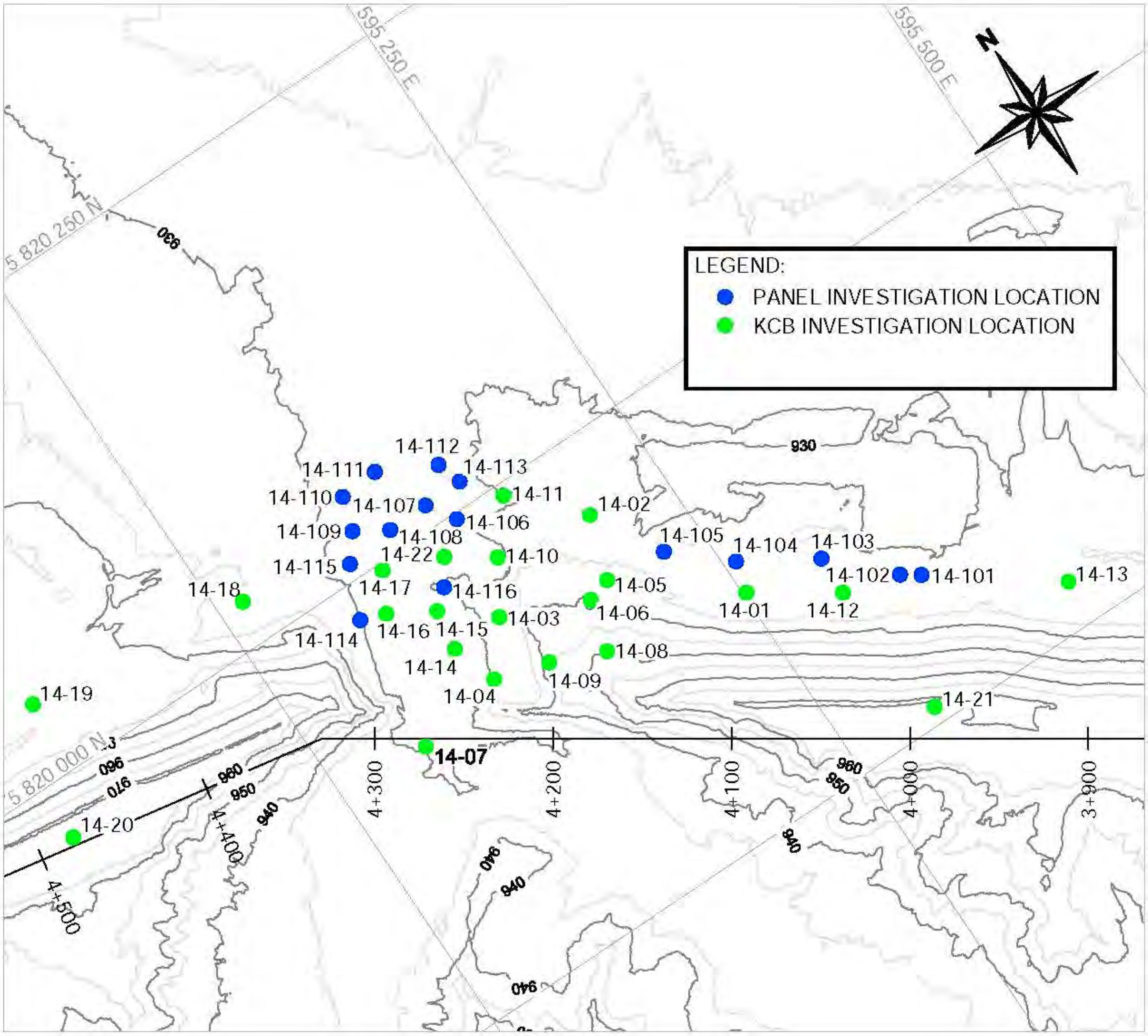
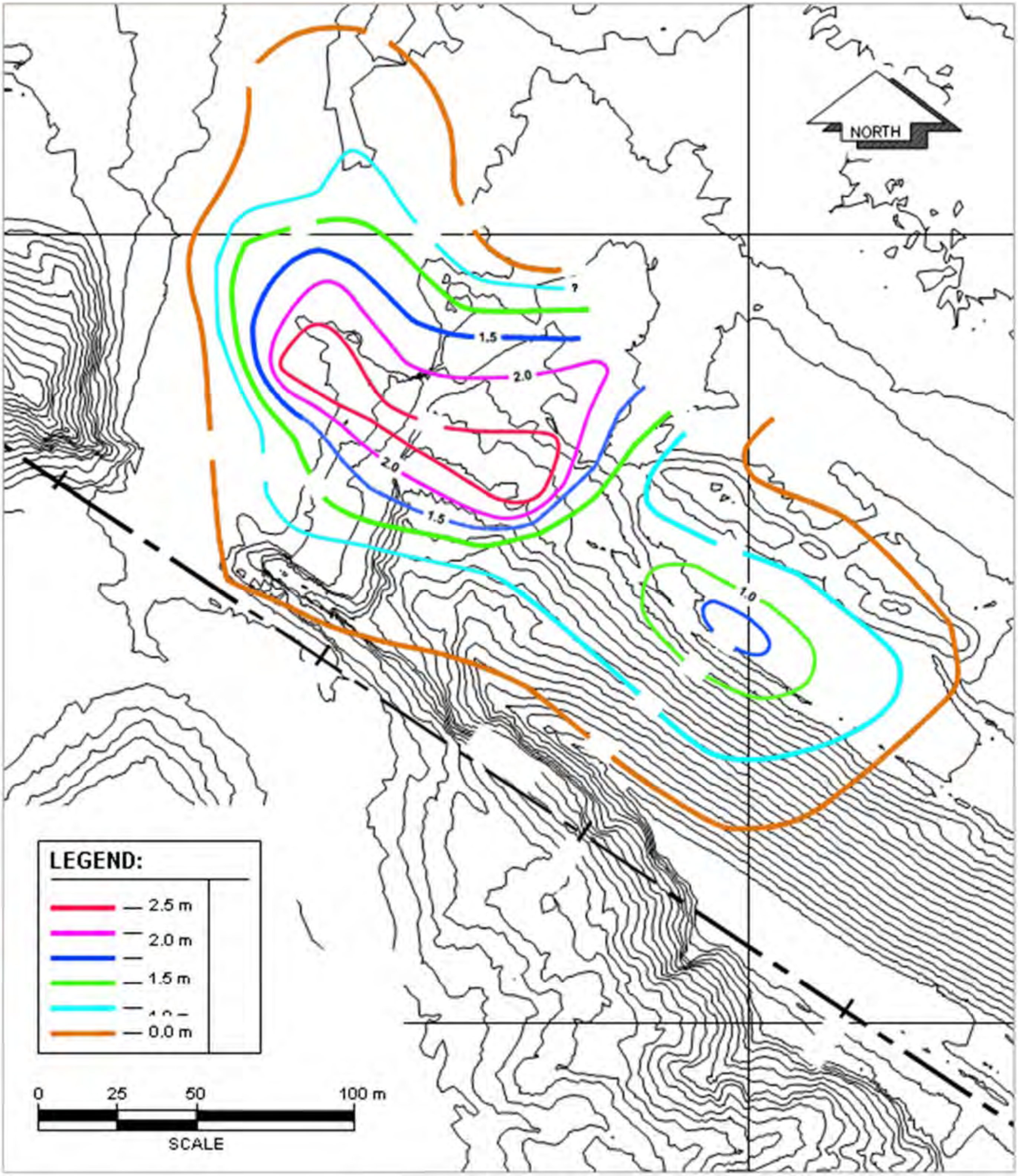


Figure 4 shows the extent and thickness of the Upper GLU – just small enough to have avoided the original deeper drillholes – but large enough to cause the catastrophe.

Figure 4: Contours of Upper GLU Thickness in Breach Area



The factors that contributed to either the dam failure, or that significantly increased the impact of the dam failure, were a bit more complex than just the inability to detect the Upper GLU. The environmental damage due to the outflow of tailings and effluent were heavily influenced by several of these other factors.

Oversteepening of the Downstream Rockfill Zone

> *The specifics of the failure were triggered by the construction of the downstream rockfill zone at a steep slope of 1.3 horizontal to 1.0 vertical. Had the downstream slope in recent years been flattened to 2.0 horizontal to 1.0 vertical, as proposed in the original design, failure would have been avoided. The slope was on the way to being flattened to meet its ultimate design criteria at the time of the incident.*

The plans for the dam originally called for a downstream slope of 2.0 horizontal to 1.0 vertical. Early on in the construction of the dam, which at the time of the failure had occurred in nine separately-approved construction events, a decision had been made to build the dam at a steeper slope (1.3 horizontal to 1.0 vertical) until enough construction rock became available to fill in the downstream "buttress" of the dam. The result was that that the steeper-sloped dam put more pressure on a smaller area, causing it to fail. As noted by the panel, if the dam had been constructed as designed, with a downstream slope of 2.0 horizontal to 1.0 vertical, the pressure from the dam and tailings would have been distributed over a greater area, and the dam would not have failed.

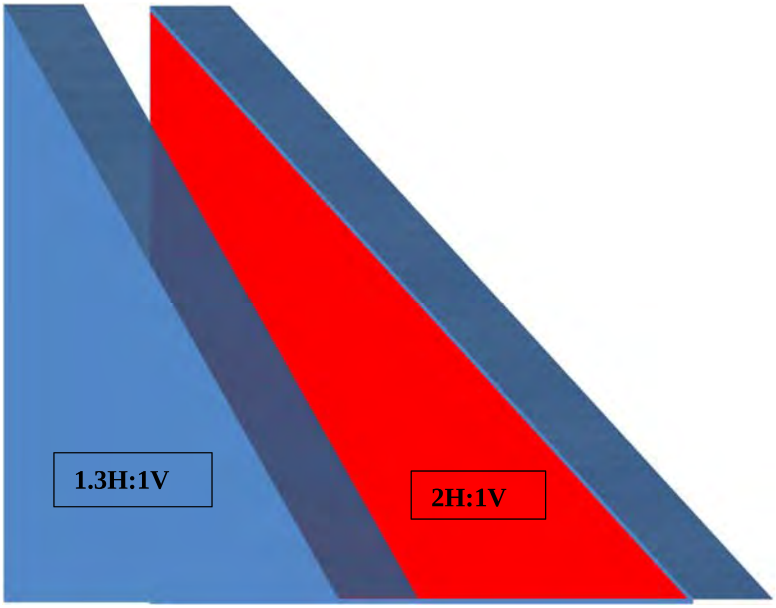


Figure 5: Tailings Dam Downstream Slopes

The panel's overall conclusion was:

> *The dominant contribution to the failure resides in its design. The design did not take into account the complexity of the sub-glacial and pre-glacial geological environment associated with the Perimeter Embankment foundation. … Hence, the omissions associated with site characterization may be likened to creating a loaded gun. Notwithstanding the large number of experienced geotechnical engineers associated with the TSF over the years, the existence of this loaded gun remained undetected.*

and;

> *If constructing unknowingly on the Upper GLU...constituted loading the gun, building with a 1.3H:1V angle of repose slope over this stratum pulled the trigger.*

and;

> *The design was caught between the rising water and the Mine plan, between the imperative of raising the dam and the scarcity of materials for building it. Something had to give, and the result was oversteepened dam slopes, deferred buttressing, and the seemingly ad hoc nature of dam expansion that so often ended up constructing something different from what had originally been designed.*

Not knowing about, and accounting for, the glacial lake clay “loaded the gun” in the panel’s words, and building the dam steeper than the design called for “pulled the trigger.”

Other Complicitous Factors

There were a number of other factors that turned up during the course of the investigation of the dam failure that contributed materially to the fundamental cause of the accident itself. However, one factor made the accident significantly worse, and two others could eventually have led to a dam failure on their own.

(1) Tailings Pond Water Level

At the time of the dam failure the water level in the tailings pond was just below the maximum level allowed. For some time the mine has been forced to manage water in the tailings pond at emergency levels due to higher than predicted precipitation

> *The high water level was the final link in the chain of failure events. Immediately before the failure, the water was about 2.3 m below the dam core. The Panel’s excavation of the failure surface showed that the crest dropped at least 3.3 m, which allowed overflow to begin and breaching to initiate. Had the water level been even a metre lower and the tailings beach commensurately wider, this last link might have held until dawn the next morning, allowing timely intervention and potentially turning a fatal condition into something survivable.*

The overflow of water due to the high water level in the tailings pond caused the mass release of tailings and contaminated water. There would have been a dam breach even absent the water, but with no water there would have been little tailings release. There would probably have been minimal or no tailings release if the tailings pond were at normal levels – but it wasn’t, and the tailings pond full of water led to the large release of tailings downstream.

Managing mine water was an issue because the water balance predictions were not accurate.

> *The water balance model included the site-specific information to the date of analysis, and future conditions were based on average climatic conditions. They did not account for specific wet year conditions.*

This is an issue that should have been apparent to both regulators and mine designers, but was either missed or ignored.

The mine had received permission to discharge treated water to resolve this problem, and a treatment plant was scheduled to begin operation in September, 2014. The accident happened on August 4, 2014.

However, earlier in 2014 the tailings pond faced a potentially catastrophic situation when water reached the top of the dam, and began to overflow. If this had continued, it too would have caused a catastrophic dam failure with concurrent release of tailings and contaminated water, much like the August accident.

Again, in order to stress the severity of the issue, here are the words of Panel:

> *For years, dam raising had managed to stay one step ahead of the rising water. But on May 24, 2014, the water caught up. With Stage 9 nearing completion, what was described as “seepage flow” was observed over the dam core. Intensive surveillance and construction activity over the following days and weeks succeeded in raising low areas around the embankment perimeter, restoring containment integrity, and saving the dam from overtopping failure.*

The problems with the water level demonstrates the multitude of threats at this site. The water level in the tailings pond did not cause the tailings dam to fail, though it caused the damage to be far worse once it did fail. But dam failure due to overtopping by water in the tailings pond was a real risk, and that almost happened on May 24, 2014.

(2) Dam Filter Material

The duty of the filter zone in the dam is to collect any seepage coming through the core and to prevent fines from migrating out of the core. In order for the dam to drain properly internally, the core, filter, and transition (to the buttress) zones must be carefully constructed. Much of the as-placed filter material at Mt Polley failed to meet applicable filter criteria and requirements for internal stability of its grading.

> *... in a sampling of as-placed Zone S filter gradations, the Panel found that 30% were too coarse to meet the … filter criterion … with only about 25% satisfying both filter and internal stability requirements.*

Figure 6: Void in left abutment (note geo-pick for size)

If the filter material is too course, it does not act as filter, but more like a drain. This can lead to voids in the core of the dam. This was essentially the cause of the Omai tailings dam failure. Had this situation been widespread, it too could have led to dam failure at Mt Polley.

And, in fact, during the field work associated with the dam failure, a serious void was discovered (Figure 6), but there was no evidence of further voids discovered during the investigation. The quality control function of dam construction was obviously not working satisfactorily. This reflects poorly on both those who constructed the dam, those who were supervising the construction (this should have been an independent party), and on the standards set by regulators, which were not tight enough to detect these errors.

(3) Inoperative Piezometers

A piezometer is a general term used for a well drilled into the dam to measure water level and pressure. Installed in the dam were 116 piezometers. Piezometers were installed in the dam foundation, in various embankment components, such as the upstream fill, core, and downstream transition zone, in drains located in the embankment and foundation, and in the tailings upstream from the embankment.

Piezometers, even if properly located and operating, would probably not been able to detect this type of failure. The piezometers at the Perimeter Embankment were located too far beyond the dam toe to provide critical data, and too far in between to cover the area where the breach occurred, so they were not able to supply information on the dam failure. However, normally they can provide an early warning that the core of the dam is compromised, and can provide warning of impending dam failures.

As early as 2009 the functionality of these piezometers had been an issue.[2] Yet as of August 2014, there were a total of 64 operating piezometers and 52 non-operating piezometers in the dam. There were nine operating and 13 non-operating piezometers along the section of the Perimeter Embankment that failed.

[2] Knight Piésold Consulting, Tailings Storage Facility Report on 2009 Annual Inspection (Ref No VA101-1/27-1, 2011), at 7.

Allowing nearly 50% of the piezometers to be non-operational should not be acceptable either to the dam operator or the dam regulators. Non-operational piezometers take a significant safety tool away from all dam observers.

(4) TSF Management and the "Observational Method"

According to the Panel:

> *The Observational Method is a powerful tool to manage uncertainty in geotechnical practice. However, it relies on recognition of the potential failure modes, an acceptable design to deal with them, and practical contingency plans to execute in the event observations lead to conditions that require mitigation. The lack of recognition of the critical undrained failure mode that prevailed reduced the Observational Method to mere trial and error.*
>
> *The Observational Method was invoked early on as the basis for design. This commonly accepted approach uses observed performance from instrumentation data for implementing preplanned design features or actions in response.*

However;

> *The Observational Method relies on measuring the right things in the right places.*

Interpreting from the Report, invoking the Observational Method allowed the dam operators, designers, and regulators to depart from implementing the planned design of the dam, most notably the allowing the Factor of Safety[3] to go from the planned 1.5 down to 1.3, by not constructing the dam buttressing on the planned schedule.

To make the Operational Method work mine designers would have to have known about the clay layer beneath the dam, but they didn't. They should have had extensive instrumentation to monitor the dam, but the instrumentation present at the mine site was not only in the wrong places, but much of it was not working.

In the view of the Panel, the Operational Method was misapplied at Mt Polly. But more succinctly, the Operational Method was probably invoked at Mt Polley in order to keep mine operation on schedule. Invoking the Operational Method eventually led to the dam failure. There appears to be no regulatory guidelines as to when the Operational Method can be invoked, or what should be done to put a dam operated under the Operational Method back on its planned track.

A (But Not Necessarily The) Way Forward

The Panel opened its recommendations by saying flatly:

> *The Panel* ***firmly rejects any notion that business as usual can continue. (emphasis added)***

The Panel goes on to explain what this means before rendering specific recommendations:

> *In risk-based dam safety practice for conventional water dams, some particular level of tolerable risk is often specified that, in turn, implies some tolerable failure rate. The Panel does not accept the concept of a tolerable failure rate for tailings dams. To do so, no matter how small, would institutionalize failure. First Nations will not accept this, the public will not permit it, government will not allow it, and the mining industry will not survive it. ... Tailings dams are complex systems that have evolved over the years. They are also unforgiving systems, in terms of the number of things that have to go right. Their reliability is contingent on* ***consistently flawless execution*** *in planning, in subsurface investigation, in analysis and design, in construction quality, in operational diligence, in*

[3] Factor of Safety is the ratio of available strength to the strength required for equilibrium.

> *monitoring, in regulatory actions, and in risk management at every level. All of these activities are subject to human error. (**emphasis added**)*
>
> …
>
> *Improving technology to ensure against failures requires eliminating water both on and in the tailings: water on the surface, and water contained in the interparticle voids. Only this can provide the kind of failsafe redundancy that prevents releases no matter what. ... **Simply put, dam failures are reduced by reducing the number of dams that can fail. (emphasis added)***
>
> *Thus, the path to zero leads to best practices, then continues on to best technology.*

The "*path to zero*" should not be interpreted literally to mean the Panel believes that achieving zero tailings dam failures is attainable for tailings dams or even tailings impoundments. It does mean the "goal" should be zero failures, and that in order to move toward this goal tailings impoundments need to be designed such that their stability does not depend on the structural integrity of a tailings dam.

Best Available Tailings Technology (BAT)

> *The goal of BAT for tailings management is to assure physical stability of the tailings deposit. This is achieved by preventing release of impoundment contents, independent of the integrity of any containment structures.*

The implication of the statement "*… preventing the release of impoundment contents independent of … containment structures.*" are significant. This explicitly says that the tailings must have structural integrity that is independent of a containment structure.

Tailings that are saturated with water do not have any structural integrity. The Panel recommends pursuing tailings disposal methods like dry tailings and underground tailings disposal, as well as the development of new disposal technologies, the possibilities for which the Panel considers "ripe" if the right incentives are put in place.

This recommendation from the Panel is nothing short of profound. While it stops short of saying explicitly saying no more tailings dams, it couldn't get any closer without saying it. The 'physical stability of the tailings must be independent of the containment structures.' While it might be argued that a deposit of wet tailings could be made free-draining after deposition, and therefore have some structural stability, tailings are not noted for being free-draining (in fact it is often argued they are self-sealing, that is do not leak pore water into groundwater underneath an unlined impoundment). And even if the tailings were free-draining, the portion of the tailings next to the dam would still depend on the dam for some stability.

The Panel specifically notes that water covers (i.e. maintaining saturated and water-covered tailings in perpetuity) should be avoided, even for potentially acid generating material, because the long-term risk of dam failure is too great. The Panel prefers to see potentially acid generating material stored in a dry manner, even if that means a concomitant increase in the need for (perpetual) water treatment. To the Panel, more water treatment is preferable to long-term wet storage. This is sobering.

In terms of how to apply BAT, the Panel made the following recommendations:

> *Implementation of BAT is best carried out using a phased approach that applies differently to tailings impoundments in various stages of their life cycle.*
>
> - *For existing tailings impoundments. Constructing filtered tailings facilities on existing conventional impoundments poses several technical hurdles. Chief among them is undrained shear failure in the underlying saturated tailings, similar to what caused the Mount Polley*

incident. Attempting to retrofit existing conventional tailings impoundments is therefore not recommended, with reliance instead on best practices during their remaining active life.

- *For new tailings facilities. BAT should be actively encouraged for new tailings facilities at existing and proposed mines. Safety attributes should be evaluated separately from economic considerations, and cost should not be the determining factor.*
- *For closure. BAT principles should be applied to closure of active impoundments so that they are progressively removed from the inventory by attrition. Where applicable, alternatives to water covers should be aggressively pursued.*

Interpreting, the Panel is saying:

❖ For existing impoundments – apply Best Applicable Practices (discussed below)

❖ For new TSFs, the recommended direction is clear – dry tailings, underground tailings disposal, or other non-wet alternatives. This raises the question of how to treat mines that are already in the proposal process, but which have not yet received regulatory approval. Reason would dictate that since "*… cost should not be the determining factor"* all new impoundments should be dry. But unfortunately, economic considerations are still the strongest driving factor in any mine proposal. This is probably the most cogent issue associated with Panel's observation that "*The Panel firmly rejects any notion that business as usual can continue*." The Panel is saying safety, not cost, should be the determining factor in waste impoundment design.

❖ For closure of existing impoundments – for existing impoundments, all closure plans should be for dry closure, not for water covers, even if this means increased and perpetual water treatment.

Best Applicable Practices (BAP)

Best Available Practices are more complex and detailed than Best Available Technologies. The Panel describes the situation thusly:

> *The safety of any dam, water or tailings, relies on multiple levels of defence. The Panel was disconcerted to find that, while the Mount Polley Tailings Dam failed because of an undetected weakness in the foundation, it could have failed by overtopping, which it almost did in May 2014. Or it could have failed by internal erosion, for which some evidence was discovered. Clearly, multiple failure modes were in progress, and they differed mainly in how far they had progressed down their respective failure pathways.*

The Panel makes a number of detailed recommendation for BAP that would impact dam designers, mine operators, and regulators. The BAP recommendation of most note is to implement Independent Tailings Review Boards (ITRB) for all large tailings dams, and that the effectiveness of an ITRB depends on the following:

- *That it not be used exclusively as a means for obtaining regulatory approval.*
- *That it not be used for transfer of corporate liability by requesting indemnification from Board members.*
- *That it be free from external influence or conflict of interest.*
- *That there be means to assure that its recommendations are acted upon.*

The Panel believes that it is essential that the reports of the ITRB "*… go to senior corporate management and Regulators.*" The Panel does not include the public as one if its suggested parties to be informed. Whether this is an intentional omission, or whether the Panel assumed that since the reports would go to regulators they would then become public records, is not clear.

The Panel made a number of very insightful observations on Best Available Practices, including:

> *The Panel anticipates that this* (adopting guidelines) *will result in more prescriptive requirements for site investigation, failure mode recognition, selection of design properties, and specification of factors of safety.*

Here the Panel is saying that more prescriptive requirements are needed to provide guidance to tailings impoundment designers and operators. This is not a recommendation that says 'less regulation,' or 'self-regulation', but a recommendation that clearly says more 'guidance' is needed from regulators.

With a broader view, the Panel also noted:

> *… future BAP require considerations that go beyond stability calculations. It is important that safety be enhanced by providing for robust outcomes in dam design, construction and operations.*

By focusing on "*…providing for robust outcomes in dam design, construction and operations.*" the Panel is saying that tailings dam design and operation must do more than just provide "*stability calculations*". Here the Panel is again demonstrating its focus on safety (in placing emphasis on determining *robust outcomes*) over cost (merely focusing on *stability calculations* for the structures that the project can afford).

The Panel notes that in its 'revised costing' approach

> *The chief reason for the limited industry adoption of filtered tailings to date is economic. Comparisons of capital and operating costs alone invariably favour conventional methods. But this takes a limited view. Cost estimates for conventional tailings dams do not include the risk costs, either direct or indirect, associated with failure potential. ... Nor do standard costing procedures consider externalities, like added costs that accrue to the industry as a whole, some of them difficult or impossible to quantify. Full consideration of life cycle costs including closure, environmental liabilities, and other externalities will provide a more complete economic picture. While economic factors cannot be neglected, neither can they continue to pre-empt best technology.*

If "*business as usual*" is to change, then a goal of zero failures which places a priority on conservative assumptions in dam/disposal design must take precedence. Safety in operation must take priority over mine production. From a project standpoint waste disposal costs must be driven by safety considerations, not by 'what the project can afford'.

#####

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"Technical Support for Grassroots Public Interest Groups"

October 16, 2017

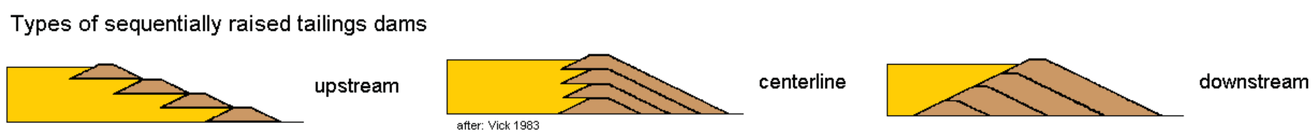
To: Kevin Lee
Senior Staff Attorney
Minnesota Center for Environmental Advocacy
klee@mncenter.org

Re: Draft Dam Safety Permit Numbers 2016-1380 and 2016-1383

COMMENTS ON DRAFT DAM SAFETY PERMIT NUMBER 2016-1380, FLOTATION TAILINGS BASIN

1. The permit allows upstream-type construction to continue.

Safety should be the prime consideration in the design, construction, operation, and closure of a dam, whether this be a water supply reservoir or a tailings dam. However, unlike water supply reservoir dams, which are typically of concrete arch-type or downstream-type construction, tailings dams can use centerline-type and upstream-type construction, each of which is inherently less safe than downstream-type dam construction.



As can be seen from the illustrations, upstream-type dam construction uses the tailings themselves for support for most of dam construction stages. Centerline and downstream-type construction, even though it is also done in stages like upstream, depends only on materials that are sized, placed, compacted, and subsequently tested for support of the sequential stages. When tailings are hydraulically spigotted into the impoundment, their placement and water content are not uniform. There is no practical way to test the characteristics of the tailings material to assure that it is subsequently drained of excess water after hydraulic placement, and that is has the consistency and density assumed by the design modeling.

This lack of control of the underlying tailings introduces a level of uncertainty into upstream-type construction that does not exist with centerline and downstream-type dam construction. This does not mean that upstream-type dams cannot be safely designed and constructed, but it does mean there is more risk inherent in the upstream approach. Moreover, it turns out that upstream-type tailings dam construction has proven to be the most risky and problematic type of dam construction.

The only reason to use both centerline and upstream construction, over a conventional downstream-type approach, is to save money. At best, it might be argued that safety and cost carry equal weight in tailings dam considerations, but today for most design, operation, and closure tailings dam considerations cost carries more weight than safety. The impoundment proposed by PolyMet is a good example of this imbalance.

The Mt Polley Expert Panel,[1] which was convened by the Province of British Columbia after the Mt Polley tailings dam failure, was asked to analyze the failure mechanisms at Mt Polley and to make recommendations on preventing such failures in the future. The Panel noted:

> *"Mount Polley illustrates that dam safety guidelines intended to be protective of public safety, environmental and cultural values cannot presume that the designer will act correctly in every case."* (Expert Panel 2015, p. 133)

In tailings dam accidents we do not see a preponderance of one or two failure causes dominating. What we see is that the number and distribution of failure type is remarkably similar. That is, overtopping, seismic failure, foundation issues, internal seepage, slope instability, and structural failure all have similar number-of-failure profiles for both active and inactive tailings dam failures (Bowker & Chambers 2016).[2] This strongly suggests there is something more fundamental than the inability to deal with the causes of one or two failure types. It suggests we have failed to recognize and address something that is affecting all of these failure types. I suggest one fundamental problem is that safety is not being given clear priority over cost in the design, construction, operation, and closure of tailings dams. This affects not only the design of tailings dams, where cost plays a dominant role, but also operational management of dams, where there it too much incentive to cut corners when times get tough. Because of these factors, we are not seeing a decrease in the rate of failures for catastrophic tailings dam failures (Bowker & Chambers 2016).

2. The permits allow water to be permanently impounded.

One of the key recommendations of the Mt Polley Expert Panel is:

> *"The goal of BAT (*Best Available Technology*) for tailings management is to assure physical stability of the tailings deposit. This is achieved by preventing release of impoundment contents, independent of the integrity of any containment structures. In accomplishing this objective, BAT has three components that derive from first principles of soil mechanics:*
>
> *1. Eliminate surface water from the impoundment.*
>
> *2. Promote unsaturated conditions in the tailings with drainage provisions.*
>
> *3. Achieve dilatant conditions throughout the tailings deposit by compaction."* (Expert Panel 2015, p. 121)

By building on top of an existing upstream-type impoundment, and/or by allowing water to pond on the tailings post-closure, the tailings facility proposed by PolyMet violates all of the recommendations listed above. The danger is leaving water on top of the tailings is 2-fold.

First, water means partial or full saturation of the tailings below. If the tailings are saturated, they have essentially no weight-bearing capacity under seismic loading. This means that any structure built on top of saturated tailings, like an upstream-type tailings dam, is susceptible to failure under seismic shaking. The permit requires further testing of the in-palace tailings to confirm assumptions used in the modeling upstream dam safety calculations, but at best, these are only interrupted samples, as opposed to an engineered structure that is required of downstream-type and centerline-type dams. It is too expensive to sample on a density that would truly provide enough data to prove that the model assumptions are

[1] Expert Panel 2015. Report on Mount Polley Tailings Storage Facility Breach, Independent Expert Engineering Investigation and Review Panel, Province of British Columbia, January 30, 2015

[2] Root Causes of Tailings Dam Overtopping: The Economics of Risk & Consequence, Lindsay Newland Bowker and David M. Chambers, International Seminar on Dam Protection Against Overtopping, Protections 2016, Fort Collins, CO, September 2016.

accurate. In addition, if the sampling shows that the modeling assumptions are incorrect, from a cost and technical perspective it is probably too late to mitigate these issues with post-deposit drains or rock buttresses.

Second, water remaining on and in the tailings acts as a deadly mobilizing agent should a catastrophic failure occur. Dry tailings can be mobilized if support is removed, but the distance they will move is orders of magnitude less than tailings saturated with water. The Mt Polley Expert Panel recognized this by remarking:

> *"Mount Polley failure shows why physical stability must remain foremost and cannot be compromised. ... No method for achieving chemical stability can succeed without first ensuring physical stability: chemical stability requires above all else that the tailings stay in one place."* (Expert Panel 2015, p. 124)

3. Does not specify dam hazard classification.

The permit specifies:

> *"The Permittee understands the hazard classification of this dam could change …"*

Not only do we not know the hazard classification being assigned to the tailings dam, but the wording also suggests that the anticipated hazard classification will not be that of the highest risk.

Because of the size of this dam, and environmental and economic destruction it could cause if it failed catastrophically, it should be classified at the highest hazard category of risk.

4. The permit does not require an Independent Tailings Review Board.

The permit does not require the use of an Independent Tailings Review Board. The use of an Independent Tailings Review Board oversight board is a recommendation of the Mt Polley Expert Review Panel.

Independent review also the recommendation of virtually every major post-Mt Polley review conducted by regulatory bodies (e.g. British Columbia, Montana, and the IFC/World Bank) and professional organizations (e.g. the Mining Association of Canada and the International Council on Mining and Metals[3]).

COMMENTS ON DRAFT DAM SAFETY PERMIT NUMBER 2016-1383, HYDROMETALLURGICAL RESIDUE FACILITY

1. The permit does not require an Independent Tailings Review Board.

As noted for the flotation tailings basin, there is no Independent Tailings Review Board oversight required. It would be simple to require an ITRB that would review both facilities.

Thank you for the opportunity to comment.

Sincerely;

David M Chambers

David M Chambers, Ph.D., P. Geop.

[3] Position Statement on Preventing Catastrophic Failure of Tailings Storage Facilities, International Council on Mining & Metals, December, 2016

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Essays and Perspectives

Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context

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ABSTRACT

After the collapse of the Fundão dam, 43 million m^3 of iron ore tailings continue to cause environmental damage, polluting 668 km of watercourses from the Doce River to the Atlantic Ocean. The objectives of this study are to characterize the Fundão Tailings Dam and structural failures; improve the understanding of the scale of the disaster; and assess the largest technological disaster in the global context of tailings dam failures. The collapse of Fundão was the biggest environmental disaster of the world mining industry, both in terms of the volume of tailings dumped and the magnitude of the damage. More than year after the tragedy, Samarco has still not carried out adequate removal, monitoring or disposal of the tailings, contrary to the premise of the total removal of tailings from affected rivers proposed by the country's regulatory agencies and the worldwide literature on post-disaster management. Contrary to expectations, there was a setback in environmental legal planning, such as law relaxation, decrease of resources for regulatory agencies and the absence of effective measures for environmental recovery. It is urgent to review how large-scale extraction of minerals is carried out, the technical and environmental standards involved, and the oversight and monitoring of the associated structures.

Introduction

One year after the collapse of the Fundão tailings dam, more than 43 million m^3 (Samarco, 2016a) of iron ore tailings are still causing environmental damage, polluting 668 km of watercourses from the Doce River Basin to the Atlantic Ocean. The volume of pollutants and the extent of ecosystems affected have assumed unprecedented proportions, involving the Brazilian Atlantic Forest – one of the world's biodiversity hotspots (Mittermeier et al., 2005), estuarine, coastal and marine environments. Furthermore, it affected other priority areas for the conservation of biodiversity and cultural heritage (MMA, 2007), such as the iron geosystems of the Quadrilátero Ferrífero (Carmo and Kamino, 2015).

In less than 48 h after the collapse of the Fundão dam, a task force was created by the Attorney General's Office of the State of Minas Gerais, whose main objective was to ascertain the facts of the environmental tragedy and the repercussions on the 17 districts and 36 municipalities directly affected by the mud wave. The Minas Gerais State Public Prosecutor's Office (MPMG) worked intensively and produced, through related teams, hundreds of technical documents and expert reports. Among these studies, the 120 technical documents of the Prístino Institute (inspection reports, technical reports, studies and maps), developed in partnership with the MPMG Geoprocessing Nucleus, identified the main environmental damage, which supported most of the results of the present work (CAOMA, 2016).

The mining company Samarco Mineração S/A (a joint venture between Vale S/A and BHP Billiton), responsible for the Fundão dam, produced technical documents stating the main emergency measures adopted and the initial planning for environmental recovery. According to the company, the emergency recovery work

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prioritized the remaining structures of the dams of the mining complex and, after that, tailings containment dams were constructed within the limits of its properties (Samarco, 2016a,b). Up to the present moment, priority has been given to the recovery of the physical environment. However, a federal agency responsible for inspection and monitoring for the purposes of environmental quality recovery, evaluated the inadequacy and inconsistency of the data presented. It stated that the actions performed by the company are still insufficient to guarantee the reduction of the damage caused by the tailings, resulting in 13 notices of infraction and an environmental fine (IBAMA, 2016a).

The main objectives of the study, based on this scenario, are: detail the structural features and possible structural failures that led to the collapse; improve the understanding of the scale of the disaster from the detailed measurement of the damage caused to ecosystems, protected areas, real estate and cultural heritage; compare and highlight this disaster in the context of global tailings dam failures; detail cases of the post-disaster actions and reflect on whether lessons had been learned about Brazilian tailings failure.

Fundão Tailings Dam: structural features and environmental damage

Structural features

The Fundão dam was one of the megastructures of the Germano mining complex, located in the municipality of Mariana, Minas Gerais, southeastern Brazil. The mining complex had an installed capacity of 23 million tons/year of iron ore concentrate. In addition to Fundão, the complex contained two more dams: Santarém and Germano, the latter being the highest dam in Brazil, with a height of 175 m and a projected volume of up to 160 million m^3 of tailings (Samarco, 2013). Open pit mines, piles of sterile material deposits, industrial plants and pipelines are also part of the Germano Complex.

The Fundão dam began operating in 2008 and was designed to contain a total of 79.6 million m^3 of fine tailings (mud) and 32 million m^3 of sandy tailings during its 25-year lifespan (SUPRAM, 2008). In November 2015, Fundão contained 56.4 million m^3 of iron ore tailings deposited in merely seven years of operation, a result of the never-before attained records of Brazilian production in the years 2013 to 2015 (IBRAM, 2015). In order to accommodate this volume, it was necessary to construct dikes, using the sandy reject itself as a construction material from the upstream embankment method (Ávila, 2012).

Unforgiving structures

Among the most common methods of tailings disposal, the one with the greatest economic advantage is the upstream embankment. However, it poses a significant challenge to the geotechnical engineer, due to the fact that water is the primary instability agent. Indeed, dams using the upstream embankment method are considered “unforgiving structures” and represent up to 66% of the worldwide reported mine tailings dams failures (Rico et al., 2008; Ávila, 2012; Kossoff et al., 2014).

According to Prieto (2014), the main disadvantages and restrictions of this technology are: foundation of later lifts is on unstable tailing slime, unused in earthquake zones; high level of monitoring using instrumentation required during operation; and recommendation that the rate of raised tailings dams be, preferably, no more than 5 m/year.

Since the beginning of the operation, in 2008, the Fundão dam had presented several anomalies related to drainage construction defects, upwellings, mud and water management errors and saturation of sandy material. In some situations, emergency measures were implemented (Samarco, 2016b), one of them known as retreat of the dam axis was begun in 2013. According to Samarco (2016b), the retreat represented: “. . . a temporary solution, it was decided to realign the dam on the left shoulder by moving it behind the section of the gallery to be filled with concrete, in order to allow the continuation of the landfill embankment. (. . .) The retreat would move the crest closer to the water of the reservoir and the mud contained within, but it was anticipated that the dam would quickly return to its original alignment once the buffering operations were done.”

However, the retreat was maintained until the collapse of the dam. According to Samarco (2016b): “As the dam embankment continued, surface upwellings began to appear at the retreat of the left shoulder at various elevations and on various occasions during 2013. The saturated mass with sandy tailings was growing, and in August 2014, the drainage carpet controlling this saturation reached its maximum capacity. Meanwhile, the mud under the landfill was responding to the increase in the load that was being deposited by the embankment. The way in which it responded, and the consequent effect on the sands, was what finally made the sands liquefy.”

Technical reports on the Fundão disaster (Samarco, 2016b) concluded that the collapse was due to liquefaction of the material, a phenomenon that occurs when solid materials (sandy tailings) lose their mechanical resistance and present fluid characteristics. Basically, the disaster occurred because of some key factors such as: structural damage to the starter dike, resulting in increased saturation; the attempt to solve structural problems with a concrete gallery that caused the axis of the dam to retract (Fig. 1), later being raised on mud; and the unforeseen deposition of sludge in critical regions. In upstream embankment dams, it is essential for the stability of the structure that the deposition of unsaturated sandy tailing create a beach, at least 200 m wide, immediately upstream of the dam crest.

Environmental and cultural damage

The total collapse of the Fundão tailings dam took place on 05 November 2015, between 3:00 pm and 4:00 pm. About 43 million m^3 of tailings (80% of the total contained volume) were unleashed, generating mud waves 10 m high, killing 19 people and causing irreversible environmental damage to hundreds of watercourses in the basin of the Doce River and associated ecosystems (Samarco, 2016b).

Most of the tailings (>90%) remained along the 120 km stretch between the Fundão dam and the hydroelectric power plant reservoir Risoleta Neves (UHE-RN), located in the municipalities of Rio Doce and Santa Cruz do Escalvado (Samarco, 2016a). The tailings remained in the Doce River channel, downstream of the UHE-RN along 548 km, reaching the Atlantic Ocean. Forty downstream municipalities were affect and hundreds of thousands of people (included indigenous) were left without access to clean water (Neves et al., 2016; IBAMA, 2015b). Therefore, in this study, the environmental damage was grouped into two sections: one upstream and the other downstream of the UHE-RN.

High resolution orthorectified satellite images (spatial resolution of 50 cm) were used to identify the environmental damage caused by the mass displacement along the 120 km upstream stretch of the UHE-RN. Two moments were compared: (1) a mosaic of images obtained prior to the dam burst (World View-2, World View-3 and GeoEye); (2) images obtained after the dam burst (World View-2, Pléiades and World View-3). The images were imported into the Geographic Information System and the elements were converted into vectors overlapping the area stained by the tailings. Information for the 548 km downstream stretch

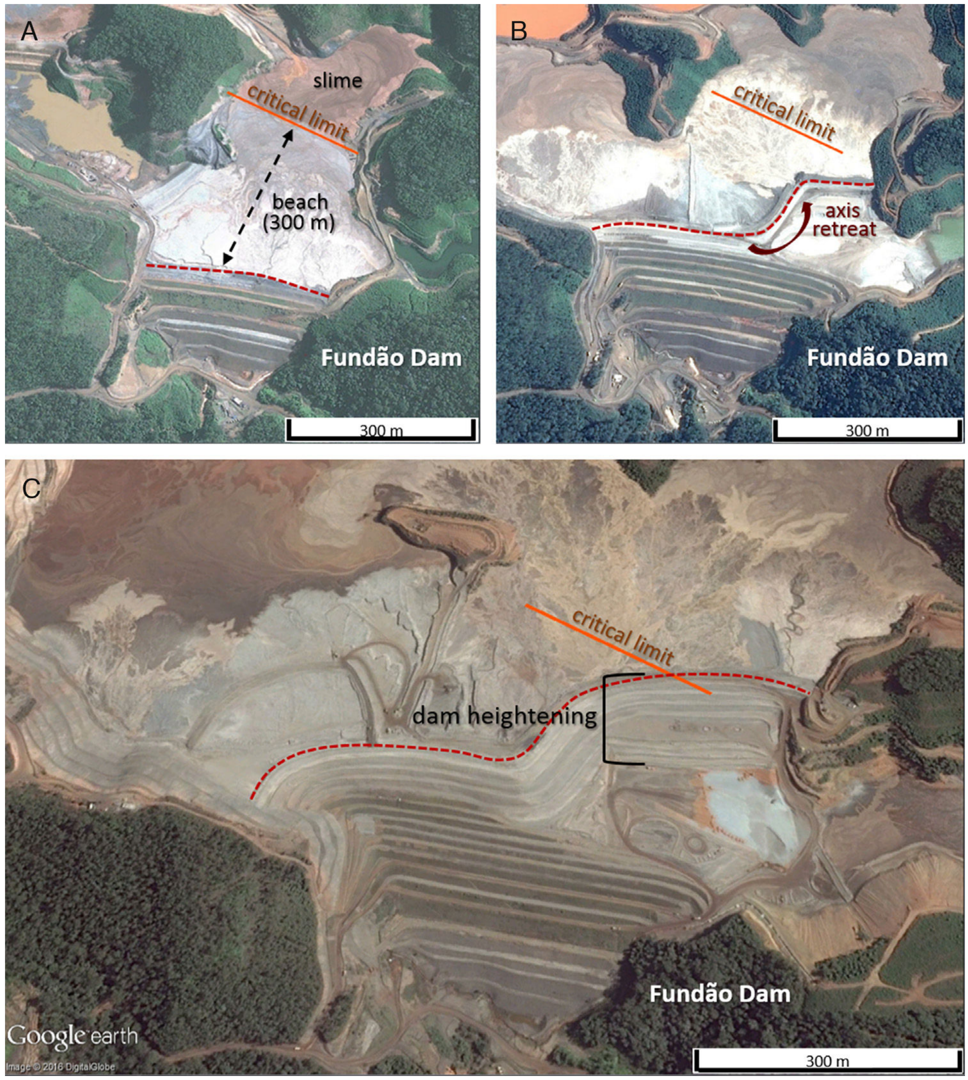

Fig. 1. Fundão dam. (A) Formation of sandy tailings beach 300 m wide and upstream mud deposition, highlighting the critical limit of contact between sandy tailings and sludge (orange line), image of 2011. (B) Retreated axis for emergency works in a concrete gallery brings the crest closer to the critical limit of contact between sandy tailings and sludge (red dashed arrow), image of 2013. (C) Embankment of the dam displaced axis in the critical limit of contact between sandy tailings and sludge (orange line), 2015 image. Adapted from *Google Earth Pro*.

of the UHE-RN, was obtained from technical reports produced by regulatory and inspection agencies and available literature.

Over a span of only 12 h, along the 120 km stretch between the Fundão dam and the UHE-RN, the mass displacement created a patch of 2020 ha and the tailings accumulated in channels, in floodplains and in the UHE-RN reservoir. This UHE-RN has not yet resumed electric power production due to the huge volume of tailings deposited in the reservoir, around 10 million m^3.

The tailings directly hit 135 identified semideciduous seasonal forest fragments, in a 298 ha of vegetation suppression, located on the banks of Gualaxo do Norte and Carmo Rivers and its tributaries. The tailings also directly hit 863.7 ha of Permanent Preservation Areas associated to watercourses, which were in protected areas, as defined by the federal forest code. Santarém Stream (11.9 km impacted), Gualaxo do Norte River (68.4 km) and Carmo River (24.7 km) were the main rivers and streams completely silted by the tailings. In addition, 294 small creeks were affected by the tailings (Fig. 2 and Fig. S1). Little attention has been given to the pollution potential of the tons of chemical compounds (flocculants and coagulants), specifically sodium hydroxide, which spilled out along with the tailings.

Out of the 806 buildings directly hit by the tailings, at least 218 were completely destroyed. These were residences, public buildings, commercial real estate, centennial churches and ancient farms distributed among 10 districts of five municipalities: Mariana, Barra Longa, Ponte Nova, Santa Cruz do Escalvado and Rio Doce. Bento Rodrigues, just 6 km from the Fundão dam, was the most damaged district with 84% of the affected buildings totally destroyed, followed by Paracatu de Baixo (40% of the buildings hit were destroyed). A total of 21.1 km of rural roads, 12 bridges/passages and the small hydroelectric plant of Bicas were also damaged.

Areas of cultural heritage also suffered greatly. Damages include, at least two archeological sites, six places of historical and cultural interest, more than 2000 sacred pieces/material heritage, five caves, a 2.2 km stretch of the Estrada Real and preserved areas of the landscape complex in the junction of the Carmo and Piranga Rivers and the urban complex of Bento Rodrigues. One of the main cultural heritage assets irreversibly affected was the São Bento chapel, an 18th-century building surrounded by stone walls (Fig. 3 and Fig. S2).

Parts of three tourist routes (*Estrada Real, Estrada Parque Caminhos da Mineração and Caminho de São José*) were also severely

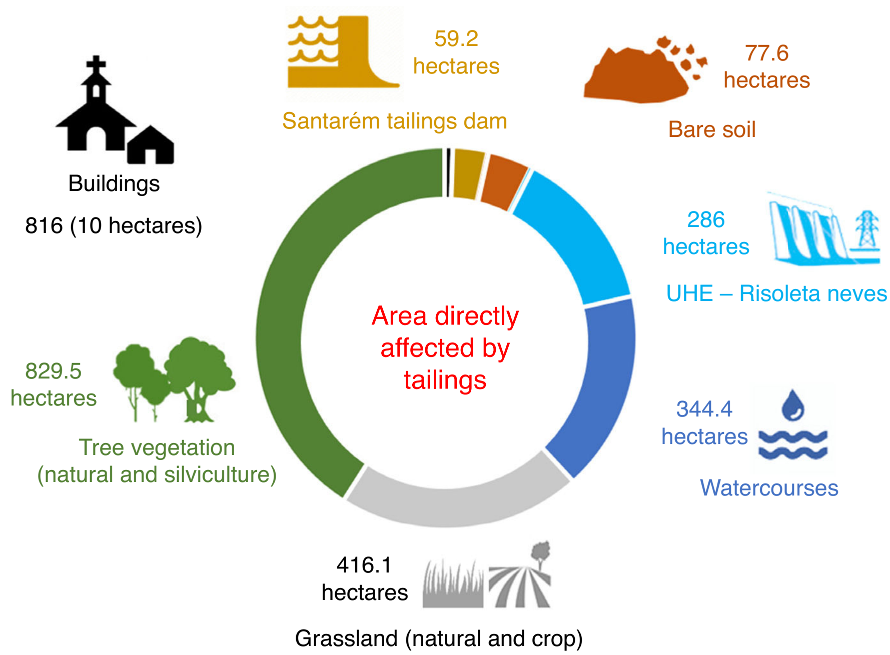

Fig. 2. Elements of natural and cultural heritage damaged by the Fundão tailings dam.

Fig. 3. Buildings affected by the Fundão tailings dam: (A) District of Bento Rodrigues, Mariana and (B) Urban area of the municipality of Barra Longa.

impacted causing losses to the local economy. The mud affected, irreversibly, areas of important archeological and speleological potential had not yet been studied, made it impossible to evaluate the exact impact on the loss of scientific knowledge.

The flood plains favored a larger accumulation of tailings (Fig. S3), on average more than 50 cm high, and in some places estimated at more than 3 m thick (Samarco, 2016a; IBAMA, 2016b). The mass displacement was so intense that it excavated the soil and altered original river beds. The tailings stain damaged four protected areas: APA Barra Longa, APE Ouro Preto/Mariana and the Biosphere Reserves of the Espinhaço Mountains and Atlantic Forest (UNESCO, 2011). There was also damage to Priority Areas for Biodiversity Conservation (MMA, 2007; Drummond et al., 2005) – named Quadrilátero Ferrífero and Florestas da Borda Leste do Quadrilátero – and in key areas for the conservation of six rare Brazilian plants (*sensu* Giulietti et al., 2009), named SE204 – Ouro Preto.

Considering that the disaster occurred in one of the most important regions for biodiversity conservation, it is estimated that the loss was significant (Fernandes et al., 2016). Tons of fish from 21 different species died in large numbers (IBAMA, 2015a). Isolated reports have identified the death of large mammals, such as the South American tapir (*Tapirus terrestris* L.), as well as turtles, birds, amphibians and invertebrates. However, no study has been published by the scientific community to account for long-term effects in main ecological components and populations of endemic species of flora and fauna.

Along the Doce River, downstream of the UHE-RN, about 5.5 million m^3 of tailings were deposited in the first days after the disaster (Samarco, 2016a; IBAMA, 2016a). Very fine tailing particles caused severe changes to the physico-chemical characteristics of the Doce River and estuarine region, increasing the turbidity levels in Minas Gerais up to 6000 times (600,000 NTU) higher than the upper limit established by law for this parameter (SEMAD, 2015). However, the impact monitoring conducted by Samarco presented very low volume of data and several physical and chemical parameters were not reported. This situation was a consequence of using inadequate methods for monitoring impacts (IBAMA, 2016c,d,e).

Three different types of sediment layers from the tailings (IBAMA, 2015a, 2016c,d,e) were detected at the mouth of the Doce River: a thick sediment deposited along the mouth; a plume deposited on the bottom; and another thinner widespread plume on the surface (floating plume). Some early projections predicted the plume would have little impact and the pollutant material would dissipate in a few months (Puff, 2015). A year after the dispersion started, 170 km of beaches were contaminated by mud, 110 km to the north of the Doce River mouth and 60 km to the south. The plumes have already spread over more than 770 km^2, having a huge effect on protected coastal zones such as the Comboios Biological Reserve, an important place for spawning of sea turtles, Santa Cruz Wildlife Refuge and APA Costa das Algas. In the

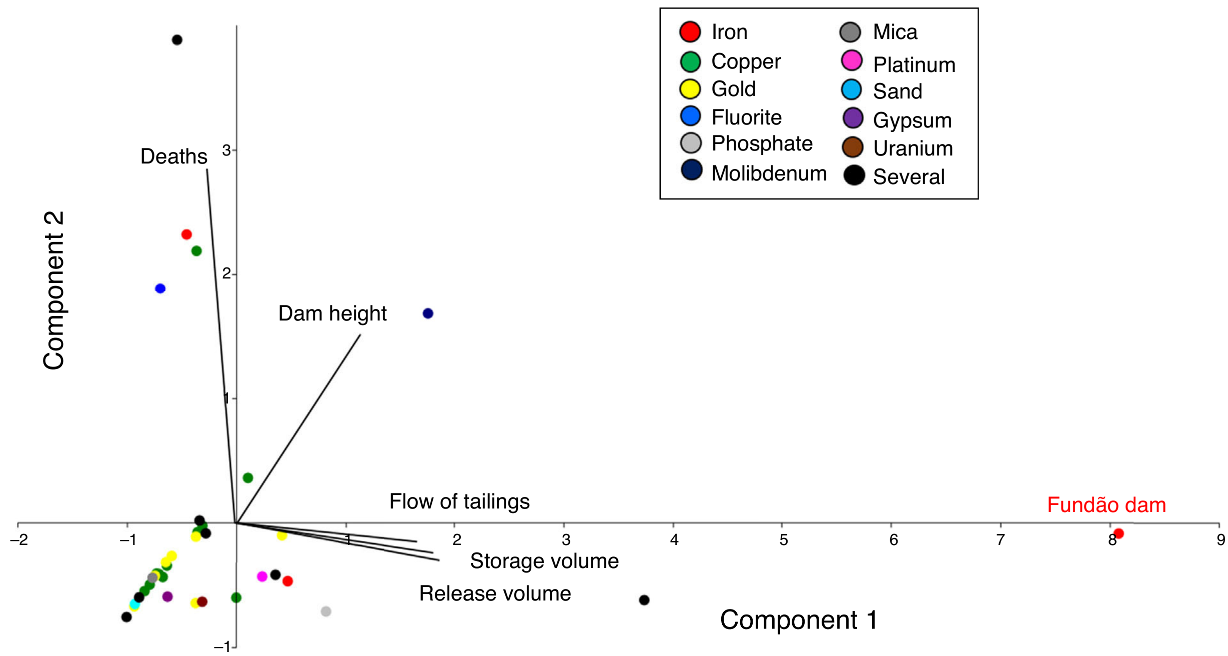

Fig. 4. Distribution pattern of 36 cases of dams disasters (colors identify the types of tailings, according to the processed ore) based on structural characteristics, distance and volume of tailing releases, and deaths by Principal components analysis. See Table S1 for details of 36 cases.

long-term, the pollution plumes could reach regions near the city of Rio de Janeiro (IBAMA, 2015a, 2016c,e; Marta-Almeida et al., 2016).

The tragedy of the largest technological disaster of Brazilian mining in the worldwide context

Based on a survey of 308 cases of mining dam collapses in the world (1915–2016, see Table S1), the Fundão dam disaster can be regarded as the largest technological disaster, considering the volume of tailings released and the geographical extension of environmental damage. The volume of tailings released by collapse of Fundão (43 million m^3) is the largest ever registered. It is followed by the one in the Philippines/1992 (32.2 million m^3); Canada/2014 (23.6 million m^3 of gold and copper residues); and Philippines/2012 (13 million m^3 of copper residues). The extent of the damage caused by Fundão is the largest ever recorded with pollutants spread along 668 km of watercourses. It is followed by the one in Mexico/2014 (420 km of contamination by copper residues), Bolivia/1996 (300 km contamination by lead-zinc residues) and Canada/1990 (168 km contamination by uranium residues).

When compared with the cases registering the highest number of deaths, the case of Fundão (19 deaths) is the ninth most serious cases of the last century. The three disasters that caused the greatest number of deaths were: Bulgaria, 1966, lead-zinc tailings (488 deaths); Chile, 1965, copper tailings (300) and China, 2008, iron tailings (277).

We used principal components analysis (PCA) to understand the distribution pattern of the dams based on structural characteristics and the main damage caused by such collapses (Table S1, Fig. 4). This study used information from about 36 cases of collapses (12% of global cases), which presented data related to the parameters: dam height, storage volume, released volume, tailings flow distance and deaths. The first two variables are technical characteristics related to the national dam safety policies (Brasil, 2010) for risk potential assessment, and the other variables represent the extent of effective damage (Azam and Li, 2010; Kossoff et al., 2014).

The first two axes of the PCA explained 53.8% and 21.9% of the variation, respectively. The variables that best explained the distribution of data in component 1 were released volume (0.96), storage volume (0.86) and tailings flow distance (0.83). The analysis indicates that most collapses are related to copper mining (11 dams), gold (7 dams) and iron mining (3 dams). Similar features keep most collapses grouped in the scatter plot (Fig. 4).

These cases exhibited distinct characteristics that make it the world's largest mining environmental disaster. However, the collapse of the Fundão dam was the most devastating and could be classified as the largest technological disaster in the context of global dam failures.

Post-disaster management

After carrying out measures for minimizing post-disaster risks, a stage involving emergency engineering work, tailings/sediments removal is considered essential and the most frequent action adopted in events of disasters with mass displacement, including collapses of mining tailings dams (UNESCO, 2010; Kossoff et al., 2014; Bowker and Chambers, 2015).

Two examples of cases of the post-disaster management to remove tailings released by the collapse of the dam occurred in Spain and in Hungary. The collapse of the dam in Andalusia, Spain, in 1998 (UNEP, 2001) released more than 2 million m^3 of zinc tailings containing sulphide-related trace elements (As, Cu, Pb, Zn and Ca) and more than 4 million m^3 of acidic water, which were deposited over 45 km of channels and floodplains on the Guadiamar and Agrio Rivers. A plan for cleaning was presented to authorities three days after the disaster with the adoption of a cleaning protocol of the affected areas (Ginige, 2014). In 12 months, about 7 million m^3 of tailings and contaminated materials that had accumulated in the river channels, floodplains and on infrastructure works were removed. The material removed was then deposited in the exhausted mining pit of the company responsible for the dam (WWF, 2002). Another case occurred in 2010 in Ajka, Hungary. Damage control action was taken after the release of over 600,000 m^3 of tailings in the environment over 14 km. The red mud was collected along the affected areas and disposed of inside a dam, which had already been reconstructed, seven days after the collapse

(Kátai-Urbán, 2010). In the medium and long term, an extensive cleaning of debris and materials dragged by the flow of tailings was conducted (Jávor and Hargitai, 2011).

Compared with cases presented, one year after the Fundão tragedy, Samarco has conducted only 0.17 million m^3 clean-up actions in urban area of Barra Longa (Samarco, 2016c), and not yet removed, monitored or properly disposed of tailings deposited in rivers, streams and flood areas. This goes against the premise of total removal of tailings in rivers affected supported by federal government. According to this premise, the company Samarco should evaluate each area regarding the possibility of total removal and proper disposal of tailings, employing alternative treatment techniques. Tailing management should only be considered as a second alternative when technical infeasibility to remove it is proven (IBAMA, 2016b).

As a wide-ranging strategy of landscape recovery (UNEP, 2001; Hudson-Edwards et al., 2003), the tailings removal should be a priority action for the regions affected by the Fundão collapse. The tailing is a source of fine inhalable particulate material, composed of minerals such as hematite, martite, magnetite and goethite. Studies show that prolonged inhalation of particulate material originated from iron mining is associated with the increase in cases of respiratory and cardiovascular diseases (Braga et al., 2007; Gomes et al., 2011). Leaching tests and toxicological bioassays performed in the region of Bento Rodrigues suggest that the tailings and contaminated soils represent a potential risk of cytotoxicity and cellular DNA damage, due to the indication of a high potential of mobilization of elements such as iron, aluminum, manganese and arsenic from the tailings into the water (Segura et al., 2016). Veronez et al. (2016) also indicate genotoxic and biochemical effects induced by iron ore, from the experimental studies which indicated the Fe and Mn accumulation can induce oxidative stress during the metamorphosis of *Lithobates catesbeianus* (L.) tadpoles.

Lessons learned?

In 2013 the Public Prosecutor's Office prepared a statement, based on a technical report from the Prístino Institute (Greenpeace, 2015), expressing concern about the risks of revalidating the Operational License of the Fundão Dam. In the statement, the Public Prosecutor's Office of the State of Minas Gerais requested that the environmental licensing body demand that Samarco carry out the following actions: perform periodic geotechnical and structural monitoring of the dikes and dam, with a maximum interval of one year between samplings; present a contingency plan in case of risks or accidents, especially in relation to the community of Bento Rodrigues, a district of the municipality of Mariana, MG; and perform rupture analysis (DAM – BREAK) of the dam, expected to be delivered to SUPRAM (Regional Superintendence of Environmental Regulation).

After the tragic environmental disaster caused by the collapse of the Fundão dam, several articles addressed a setback in the environmental legal regulations. Law relaxation, the decrease of resources for regulatory agencies and the absence of effective environmental recovery measures were often mentioned (Fearnside, 2016; Fernandes et al., 2016; Garcia et al., 2016; Wanderley et al., 2016).

In addition to the legal regulation, the case of the collapse of the Fundão dam made clear that the structures built using the upstream embankment method, widely used in Minas Gerais and Brazil, bring several environmental and social risks, which are no longer acceptable as management techniques to deal with mining waste and residues.

The Brazilian legal system includes principles that demand that entrepreneurs as well as environmental licensing bodies adopt the Best Available Technologies (BAT) to protect the constitutional rights to an ecologically balanced environment for the present and future generations, under art. 225 of the CR/1988 c/c art. 2nd and 4th of Law 6938/1981 (Loubet, 2015).

In Brazil, the dimension of the risk generated by the method in question inspired the NBR 13028, of the Brazilian Association of Technical Standards (ABNT), which deals with the "development and presentation of dam projects for the disposal of tailings, sediment containment and water reservation". This standard states the conditions required for the development and presentation of a project of tailings disposal, in dams and in mining, to comply with conditions of safety, hygiene, functionality, economy, abandonment and minimization of impacts to the environment, within the legal standards. In its 1993 version, item 4.2, clearly states: "the construction of dams using the upstream embankment method is not recommended". For reasons unknown, in the 2006 version of the same standard, this recommendation no longer appears. The Public Ministry, to guarantee that the construction of dams using the upstream embankment method be avoided, filed a legal action against the State of Minas Gerais to prevent the public administration from granting or renewing environmental licenses for this type of dam structure.

In July 2016, a bill was presented by popular initiative to the Legislative Assembly of the State of Minas Gerais establishing safety standards for mining tailings dams. The draft dealt with the improvement of dam risk management. In October 2016 the bill was already being considered in the State Legislature under PL number 3695/2016.

World disasters caused by mining tailings are closely related to the increase in demand for mineral commodities by global markets, leading to a high rate of disasters occurring in a period of 24–36 months after a soar in overall prices (Davies and Martin, 2009), which was exactly the case of Fundão. Bowker and Chambers (2015) highlighted the recent increase in the rate of severe and very serious disasters caused by tailings dam failures and argued that this trend is a consequence of modern technologies that allow the exploitation of reserves with even smaller ore concentrations. This situation results in a huge increase in the storage capacity of mining tailings dams (Wanderley et al., 2016). Bowker and Chambers (2015) estimate society's billion-dollar costs related to disasters caused by tailings dams and highlight the urgent need for changes in regulatory systems to fit this global trend.

Apart from its sheer magnitude, the collapse of Fundão is the seventh such case that has occurred in Minas Gerais alone since 1986 (Felippe et al., 2016). There is an undeniable need to review environmental standards, for more rigorous control of the hundreds of mining tailings dams in Brazil. In addition, it is fundamental to review how large-scale mineral extraction is carried out, as well as to encourage the use of alternative technologies for the disposal of tailings such as disposing of them in abandoned caves or dewatered stockpiling (dry stacking) for tailings disposal (Gomes et al., 2016). These measures may contribute to minimize the conversion of new, natural areas into megastructures to contain tailings, and to avoid the potential risk of environmental damage to creeks and rivers and associated ecosystems.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pecon.2017.06.002.

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October 16, 2017

FILED ELECTRONICALLY

Tom Landwehr, Commissioner
Minnesota Department of Natural Resources
500 Lafayette Road
St. Paul, MN 55101

RE: Comments on PolyMet Draft Dam Safety Permits 2016-1380 and 2016-1383

Dear Commissioner Landwehr,

The following comments are submitted on behalf of WaterLegacy, a Minnesota non-profit formed in 2009 to protect Minnesota's water resources and the communities who rely on them.

WaterLegacy believes proceeding with draft PolyMet Dam Safety permits released for public review by the Minnesota Department of Natural Resources (DNR)[1] is premature and inconsistent with the obligation under Minnesota rules, "to regulate the construction and enlargement of dams, as well as the repair, alteration, maintenance, operation, transfer of ownership, and abandonment, in such a manner as to best provide for public health, safety, and welfare." Minn. R. 6115.0300.

The current PolyMet draft Dam Safety permits are inadequate and must be denied based on Minnesota statutes that only allow issuance of a permit if the commissioner concludes that the plans of the applicant are reasonable "and will adequately protect public safety and promote the public welfare." Minn. Stat. §103G.315, Subd. 3. PolyMet dam permits must also be denied based on Minnesota dam safety permit rules, which base approval or denial on "potential hazards to the health, safety, and welfare of the public and the environment." Minn. R. 6115.0410, Subp. 8. Grounds for denial of the draft PolyMet Dam Safety permits are summarized below.

1. PolyMet has not performed studies of the potential hazards that would result from dam failure at its proposed Flotation Tailings Basin (FTB) or Hydrometallurgical Residue Facility (HRF) dams. PolyMet has also failed to complete materials studies related to the risk of failure of the FTB dam and has used unfounded assumptions in place of analysis of the risk of failure of the HRF dam.

2. Draft PolyMet Dam Safety permits defer regulatory decisions that should be contained in permits and fail to provide conditions, final design requirements or specific contingencies

[1] Draft Permits for the Flotation Tailings Basin (2016-1380) ("FTB Draft Dam Permit") and the Hydrometallurgical Residue Facility (2016-1383) ("HRF Draft Dam Permit") are available on the MDNR website, respectively, at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/2017-0915-draft-2016-1380.pdf and http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/2017-0915-draft-2016-1383.pdf.

needed to regulate construction, maintenance, operation and abandonment of the FTB and HRF dams to protect public health, safety, welfare and the environment.

3. Draft FTB and HRF Dam Safety permits, along with the PolyMet documents incorporated by reference in the draft permits,[2] fail to provide adequate factors of safety, to comply with Minnesota rules or to address well-founded concerns, including those of DNR's consultants, regarding fundamental design of PolyMet waste facilities.

PolyMet's FTB and HRF sulfide mine waste dams would be permanent fixtures affecting the Partridge River and Embarrass River tributaries and wetlands in the headwaters of Minnesota's St. Louis River. Dam breach or failure, release of sulfide mine tailings waste or release of toxic and concentrated hydrometallurgical waste could affect these headwaters and downstream waters of the St. Louis River, the largest U.S. tributary to Lake Superior. Waters downstream of PolyMet's proposed FTB and HRF dams include Colby Lake, the source of drinking water for the city of Hoyt Lakes, fisheries in the St. Louis River, the St. Louis River estuary, and Lake Superior. Communities potentially affected by the release of PolyMet wastes include the Fond du Lac Reservation and Duluth, Minnesota's third largest city.

More than any other mine features, the PolyMet mine tailings waste and hydrometallurgical residue dams are things that could go catastrophically wrong at the PolyMet copper-nickel mine project. The draft PolyMet Dam Safety permits fail to meet the State's fiduciary obligation to protect Minnesota citizens, drinking water, environment, fisheries, private property and human health from potential contamination and devastation. These permits must be denied.

1. Failure to Perform Critical Studies to Protect Public Safety, Health, Welfare and the Environment.

A. Flotation Tailings Basin

Tailings dams fail at a rate that is approximately 10 times higher than that of water supply reservoir dams.[3] Upstream-type dam construction, which is the type of construction proposed for the PolyMet tailings dam, poses the highest risk for both seismic and static failure, and most tailings dam failures have been associated with upstream construction.[4] These facts and the

[2] DNR Commissioner Landwehr has confirmed in a Sept. 29, 2017 letter attached as Exhibit 1 that the draft PolyMet FTB dam permit incorporates by reference the NorthMet Project Geotechnical Data Package ("FTB Geotech.") and the NorthMet Project Flotation Tailings Management Plan ("FTB Mgt. Plan") in Appendices A and B of PolyMet's May 2017 NorthMet Dam Safety Permit Application for the Flotation Tailings Basin, available at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/v2/dam_safety_permit_application_flotation_tailings_basin_v2_may2017.pdf and that the draft PolyMet HRF dam permit incorporates by reference the July 11, 2016 Geotechnical Data Package – Volume 2-Hydrometallurgical Residue Facility ("HRF Geotech.") available at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/references/geotech_data_package_vol2_hrf_v6.pdf and the Residue Management Plan - Hydrometallurgical Residue Facility ("HRF Mgt. Plan") in Appendix A of PolyMet's May 2017 NorthMet Dam Safety Permit Application for the Hydrometallurgical Residue Facility ("HRF Permit Application") at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/v2/dam_safety_permit_application_hydromet_residue_facility_v2_may2017.pdf?utm_content=&utm_name=&utm_term=

[3] David Chambers, Comments on the Geotechnical Stability of the Proposed NorthMet Tailings Basin and Hydrometallurgical Residue Facility in light of the Failure of the Mt Polley Tailings Storage Facility, April 30, 2015, p. 2, (WaterLegacy FEIS Comments, Exhibit 21, incorporated by reference *infra* in footnote 5)

[4] *Id.*, pp. 2-3.

recent experience of serious and very serious dam failure, all of which were detailed in WaterLegacy's comments on the PolyMet NorthMet Final Environmental Impact Statement,[5] underscore the importance of a rigorous and complete dam break analysis to evaluate design choices and mitigation strategies as well as potential hazards that may be critical to the decision whether to approve or deny dam safety permits.

Inadequate Dam Failure Analysis

The PolyMet dam break analysis upon which the draft FTB dam permit relies has a very limited scope. The sole purpose of this analysis,[6] a mere 13 pages prepared in 2012 and not updated since then, was to develop an emergency action plan to notify the property owners living in closest proximity to PolyMet's proposed tailings waste storage facility in the event of a breach. This is one of the legitimate reasons for doing a dam break analysis, and PolyMet's analysis provides information on the number of homes that could be affected by a modest dam breach to the north.[7]

However, PolyMet's dam break analysis is inadequate to answer the questions asked in Minnesota rules to determine the hazard classification of dams and the adequacy of dam safety permits. Minn. R. 6115.0410, Subp. 8. Years after catastrophic failure of tailings dams, including the Mount Polley copper tailings dam in Canada, PolyMet's meager analysis ignores the greatest threats posed by the failure of its proposed tailings waste dam: downstream water quality, public health, safety, welfare and the environment. At minimum, the following questions must be answered before any PolyMet tailings waste dam permit could be appropriately considered:

- What potential hazards would result from a PolyMet dam breach or failure involving mobilization and flow of tailings waste?
- What potential hazards would result from a PolyMet tailings dam collapse rather than an assumed breach of limited scope?
- What potential hazards to wetlands, municipal water supplies, water quality, fisheries, environment and human health would result from a PolyMet tailings dam failure?
- What potential hazards would result from a dam failure on the south side of the PolyMet FTB (Cross-Section N), adjacent to Second Creek?

PolyMet has admitted that its dam break analysis provides no information on the extent or consequences of tailings release and flow in the event of a breach - due to its limited purpose:

> Extensive additional analysis would be necessary to realistically estimate the percentage of flotation tailings left in the FTB, to evaluate flotation tailings deposition after the breach and to better understand flow properties of the liquefied flotation tailings. Such

[5] WaterLegacy's Comments ("WaterLegacy FEIS Comments") on the November 2015 PolyMet NorthMet Final Environmental Impact Statement ("PolyMet FEIS") and its associated expert reports, FEIS Exhibits 1-36, and Appendix containing Comments on the PolyMet NorthMet Supplemental Draft Environmental Impact Statement (SDEIS) with its associated expert reports and SDEIS Exhibits 1-54 provided to the DNR on CD December 14, 2015 are herby incorporated by reference.

[6] Barr Technical Memorandum, FTB Dam Break Analysis, Dec. 4, 2012, Attachment H of FTB Mgt. Plan ("FTB Dam Break Analysis").

[7] *Id.*, p. 8.There would be 34 homes along Trimble Creek or breakout paths that could be affected by the modeled dam break.

> analysis is not warranted given the objective of this dam break analysis, which is to serve as an aid in development of the facility Emergency Action Plan.[8]

PolyMet has also acknowledged the significance of questions about the volume of tailings that would be suspended and carried downstream in the event of a dam breach:

> The most significant unknown breach parameter for a tailings basin dam is how much of the tailings would be suspended and carried downstream in the event of a dam breach. Studies have shown that in many cases only 30 percent of the volume in the basin is carried downstream, however basin dam breaks have been recorded where up to 80 percent of the volume was carried downstream.[9]

Despite the importance of evaluating the release of tailings in the event of a dam breach, PolyMet's used a dam break model, the HEC-HMS computer model, which can only model water release, not tailings mobilization and flow.[10] DNR's senior dam safety engineer, Dana Dostert, while finding the dam analysis appropriate for developing a contingency notification plan, expressed concern that the only analysis done by PolyMet was for a water breach. "I have never been completely comfortable with it as it dealt with a water breach. An actual failings that mobilized tailings would be much more serious."[11]

There are several well-known software programs available to model mine tailings and other non-Newtonian liquids, including DAMBRK, FLO-2D, FLDWAV, and DAN-3D.[12] Particularly in light of the catastrophic failure and release of tailings at the Mount Polley dam in British Columbia, Canada and at the Fundão Dam in Samarco, Brazil,[13] the DNR must require that PolyMet perform new modeling of potential hazards posed by a FTB dam breach using software designed to reflect the characteristics of tailings.

Next, PolyMet's limited 2012 dam break analysis only pertains to a small break in the north side of the tailings waste dam as a result of a piping-initiated dam failure on the North Dam of Cell 2E.[14] PolyMet's analysis does not reference current FTB designs and concerns with cross-sections F, G and N and with potential liquefaction, highlighted in PolyMet reports since 2012.[15] Although the FTB would cover four-and-a-half square miles and extend for more than a mile

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[8] *Id.*, p. 7.
[9] *Id.*, pp. 6-7.
[10] Model is cited *Id.*, p. 2. The HEC-RAS model is described in USACE, Using HEC-RAS for Dam Break Studies, TD-39, August 2014, available at http://www.hec.usace.army.mil/publications/trainingdocuments/td-39.pdf
[11] D. Dostert, DNR Review of PolyMet's Dam Safety- Tailings Basin – Permit Application, Contingency Action Plan, undated, attached as Exhibit 2.
[12] *See e.g*. Bernedo, Predictive Models & Available Software, USSD Workshop on Dam Break Analysis Applied to Tailings Dams (2011), p. 11-24. http://www.infomine.com/library/publications/docs/bernedo2011.pdf, attached as Exhibit 3.
[13] *See* WaterLegacy FEIS Comments, *supra*, pp. 69-72, WaterLegacy FEIS Exhibits 19, 20, 21, 25, 26 incorporated by reference in footnote 5, and news articles attached in Exhibit 4 to these comments.
[14] FTB Mgt. Plan, p. 20,
[15] *See e.g.,* FTB Geotech., pp. 8, 39, 63, 91, 111, 117.

along its north side,[16] the breach width for PolyMet's dam break analysis was assumed to be less than 450 feet wide.[17]

PolyMet' dam break analysis fails discuss the potential of a more significant dam collapse in the event of tailings liquefaction. Even without a seismic trigger, PolyMet has admitted that both its own flotation tailings and the LTVSMC fine tailings and slimes beneath them could liquefy:

> A seismic triggering event (earthquake) occurs globally and instantly impacts all soils. Global static liquefaction could also be induced by high porewater pressures associated with a large storm event or if the entire slope was unintentionally steepened during construction. The potential for LTVSMC fine tailings and slimes and the Flotation Tailings to liquefy in response to triggering events is due to the fact that some of these materials are hydraulically deposited and come to equilibrium under very loose to loose conditions.[18]

For the DNR to evaluate potential FTB hazards, PolyMet must analyze the consequences of a catastrophic dam failure releasing sulfide mine tailings waste.

Next, tailings dam breach analysis must be sufficient to address statutory permitting factors pertaining to public health and the environment, not only the timing of notification to property owners whose homes lie closest to a potential breach. In order to determine potential hazards to public health, safety, welfare and the environment, as required by Minnesota statutes and rules, the DNR must require PolyMet to analyze impacts of the release of contaminated water and tailings slurry - with the chemical composition predicted for the PolyMet flotation tailings - on wetlands, drinking water supplies, surface waters, fish and wild rice downstream of the proposed PolyMet FTB. In addition, to the extent that municipal water and fish would be contaminated with heavy metals such as lead, arsenic and methylmercury in the event of dam failure, the DNR must require PolyMet to evaluate the human health and municipal economic costs of dam failure and downstream contamination.

Finally, in order to evaluate potential hazards to public health, safety, welfare and the environment, the DNR must require that PolyMet conduct a dam break analysis on the south side of its proposed FTB. PolyMet justified its sole focus on the north side as follows:

> The dam break analysis focused on the north side of the FTB, because this is the section of the dam where a break would result in the shortest warning time for potentially affected downstream properties. A breach was not considered to the east or south of the FTB because a large portion of the perimeter ties into natural ground and/or no homes are within the respective downstream flow path.[19]

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[16] *See* Figure B-1 in Attachment B to FTB Geotech., included as Exhibit 5 of these comments.
[17] FTB Dam Break Analysis, *supra*, p. 6: The average breach width was assumed to be 2.24 times the height of the dam and the depth of the breach was calculated at 134 feet. Breach width was estimated based on dam height of 200 feet stated in the FTB Dam Break Analysis, *supra*, p. 4.

[18] FTB Geotech., pp. 71-72.
[19] FTB Dam Break Analysis, *supra*, p. 4.

The south side of the proposed PolyMet FTB dam may not be as close to private homes as the north. But, PolyMet's proposed Cross-Section N, a section through the south perimeter dam of FTB Cell 1E, is immediately adjacent to Second Creek, near wetlands and near the proposed corridor for the Colby Lake Water Pipeline.[20] A dam failure at this location could have devastating consequences related to contamination of water, fish and wild rice and, potentially, municipal drinking water drawn from Colby Lake by the city of Hoyt Lakes.
The PolyMet dam break analysis, modeled without consideration of tailings mobilization or deposition, restricted to the purpose of notifying nearby property owners, limited to a small discrete breach and focusing only on one potential dam cross-section is inadequate to advise decision-makers or the public of the risks of tailings waste dam failure so that appropriate decisions may be made on hazard classification and permitting approval, denial or conditions. The DNR has a duty under Minnesota Rules and a fiduciary responsibility to require a new dam breach analysis that models tailings mobilization and flow, analyzes the results of catastrophic failure, and describes water contamination and other environmental hazards resulting from either a north or a south FTB dam failure.

Inadequate Materials Data
In addition to inadequacies in PolyMet's FTB dam breach analysis, review of the Geotechnical Data Package suggests several gaps in basic materials data needed to determine FTB dam safety. PolyMet collected only a limited amount of fine tailings for materials testing.[21] PolyMet stated it was unable to effectively measure undrained shear strength of fine tailings, so this property was estimated.[22] Due to poor quality of compression test data, some deformation analysis was also based on estimates.[23] PolyMet failed to get samples of glacial till during its 2014 investigation.[24] PolyMet secured very little boring data from the center of the tailings basin; data were limited to two test locations.[25]

With respect to its own flotation tailings, PolyMet conducted only a small number of tests on these materials and combined coarser grinds from 2005 with more recent 2009 pilot plant tailings,[26] further reducing the usefulness of permeability data. Finally, even though PolyMet was required to analyze dam safety at Cross-Section N, PolyMet states that they have done no borings down to bedrock in this cross-section adjacent to Second Creek, so depth of till to bedrock can only be assumed.[27]

Given the number of years PolyMet has pursued its mine project, it strains credulity that basic materials data needed to determine dam stability is not robust and readily available to regulators. The DNR should require PolyMet to produce and disclose reliable data on materials and site conditions before proceeding any further with draft permits.

B. Hydrometallurgical Residue Facility

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[20] See Figure B-1 of Attachment B to FTB Geotech., *supra,* Exhibit 5, and Figure 4.2.3-1 of the PolyMet NorthMet FEIS, attached as Exhibit 6 to these comments to show locations of features near the south dam of the FTB.
[21] FTB Geotech., p. 37.
[22] *Id*., p. 16.
[23] *Id*., pp. 17-18.
[24] *Id*., p. 20.
[25] *Id*., p. 39.
[26] *Id*., p. 43.
[27] *Id*., p. 94.

The PolyMet hydrometallurgical residue facility (HRF) "dam break analysis"[28] is yet more deficient than that for the FTB. PolyMet simply declines to disclose any consequences at all of any dam breach or failure at the HRF, alleging that no potential hazards need be discussed, since various failure scenarios are "improbable" or "have a low probability" of occurrence.[29]

Engineers retained by the DNR to review HRF dam safety seem to take the potential for HRF dam failure seriously due to inadequacy of the foundation beneath the proposed HRF and the risk of liner deformation. The EOR Dam Safety Review team cautioned in May 2017, "The soft ground beneath the proposed residue facility consists of up to 30 feet of slimes, peat and tailings concentrate. This will not be an adequate foundation for the 80 foot high basin."[30] The Review further noted, "The basin will have a geomembrane or geosynthetic liner. The liner could deform and fail if the existing underlying material cannot support the material added to the basin."[31]

Modern standards for dam break analysis also contradict PolyMet's theory that decision-makers and the public need not know the consequences of dam failure if the project proponent asserts that failure is "improbable." Since the Mount Polley and Samarco tailings breaches released toxic slurries downstream, it is widely recognized within the industry that "Dam breach and inundation studies are an important aspect of dam safety procedures. . . The major benefit of dam breach studies, no matter how improbable the results may be, is that they trigger discussions on various possible measures to reduce the risk of a breach."[32] Government agencies also advise, "In the context of risk informed decision making, dam breach analyses are needed for determining the potential consequences of a failure mode's occurrence over a range of loading conditions. It can also be used as part of a dam's remedial design process in the selection of alternatives."[33]

Minnesota Rules require that PolyMet produce a meaningful dam breach analysis for its proposed HRF dam to enable regulators to determine its hazard classification. By rule, the degree of hazard is determined not by the probability of dam failure, but by the probability that potential hazards, including damage to health and indirect economic loss, would result in the event of dam "failure, misoperation, or other occurrences or conditions." Minn. R. 6115.0340.

Even a casual reading of the record pertaining to the HRF suggests that the potential hazard should the HRF dam fail is quite serious. Approximately 313,000 tons of highly concentrated residue would be deposited annually in the HRF if PolyMet were to process all nickel flotation

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[28] Barr, HRF Dam Break Analysis, July 11, 2016, Attachment L to HRF Mgt. Plan.
[29] *Id.*, p. 4, "[H]ydrologic and hydraulic modeling to detail the extent of inundation from an HRF dam break is not warranted because no plausible HRF dam failure scenarios have been identified." *See also* pp. 2.
[30] EOR (Emmons & Olivier Resources) Review Team, PolyMet Dam Safety Permit Application Review, May 15, 2017, p. 5, MDNR website at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/memo_dam_safety_permit_review20170515.pdf
[31] *Id.*, p. 6.
[32] Martin et al., Challenges with conducting tailings dam breach assessments, 85th Annual Meeting International Commission on Large Dams (ICOLD) (July 3-7, 2017), §3.1.3, attached as Exhibit 7.
[33] FERC Engineering Guidelines Risk-Informed Decision Making, Dam Breach Analysis, Ch. R21, Draft 2014, p. 2. https://www.ferc.gov/industries/hydropower/safety/guidelines/ridm/eng-guide/chapter-R21.pdf, excerpt in Exhibit 8.

concentrate streams it plans to produce.[34] Although PolyMet insists that its concentrated residue waste would not be "hazardous," PolyMet admits that HRF waste would be acidic, and over the long term acid generation would likely be greater than neutralizing capacity.[35]

Given the concentrated and potentially toxic nature of the HRF waste, WaterLegacy finds it troubling that neither the PolyMet FEIS nor any documents supporting the DNR's draft HRF dam permit clearly set forth the constituents of the proposed HRF waste, the acidity of that waste or the mass and concentrations of sulfates and toxic metals that would be contained in that waste. Suggestive information can be gleaned from various documents as to the potential concentrations of HRF wastes.

The DNR, along with other Co-Lead Agencies for the FEIS, has stated that 164 pounds of mercury would be deposited in the HRF each year.[36] Over a 20-year mine life, up to 3,280 pounds of mercury could, thus, be deposited in the HRF. PolyMet technical reports state that hydrometallurgical residue would have sulfate levels of 7,347 milligrams per liter.[37] The FEIS also proposed that sludge from wastewater treatment would be stored in the HRF.[38] Sludge from wastewater treatment reject concentrate could contain concentrations of arsenic, lead, manganese, copper and other metals as much three orders of magnitude above applicable water quality standards.[39]

DNR's Area Fisheries Supervisor has expressed concerns about downstream hazards that would result from release of waste from the HRF, particularly over the long term:

> How long does such a liner last and what happens when it inevitably degrades as nothing lasts forever? Even if it takes 200 years, the waste will still be there and in its location would be very susceptible to leaching into nearby wetlands and groundwater. There is no mention of the expected longevity of the liner and leakage system in the long term closure description. There is mention of a monitoring plan but no mention of how the liner could be maintained or repaired or replaced. . . I don't understand how a liner could be replaced, or even repaired, under a 97 acre site with 50 feet of fill on top. . . The Hydrometallurgical Residue Facility is a concern to Fisheries because of its potential impact on water quality as the system ages.[40]

Even though a draft PolyMet HRF dam permit proposes to authorize permanent storage of concentrated and toxic waste on top of wetlands adjacent to St. Louis River tributary streams,

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[34] HRF Mgt. Plan, p. 2. The HRF would receive up to a total of 6,170,000 total tons of this waste. PolyMet FEIS, 3-117, available at http://www.dnr.state.mn.us/input/environmentalreview/polymet/feis-toc.html
[35] HRF Mgt. Plan, p. 6.
[36] PolyMet FEIS, A-414.
[37] February 2007 PolyMet RS33/RS65 Hydrometallurgical Residue Characterization, February 2007, provided to DNR in Appendix to WaterLegacy FEIS Comments as SDEIS Exhibit 27, *see* footnote 5.
[38] PolyMet FEIS, 3-53, 5-101 and Figures 3.2-12, 3.2-13, and 5.2.2-20. No HRF dam permit documents discuss whether PolyMet still plans to deposit wastewater sludge in the HRF.
[39] See PolyMet FEIS reference PolyMet 2015m, at autop. 452, data showing wastewater reject concentrate, even before it is dewatered would contain: 1,150 µg/L of arsenic (2 µg/L criterion for drinking water); 16,600 µg/L of manganese (100 µg/L HRL for drinking water); 847 of cobalt (5 µg/L surface water limit); 11,600 µg/L of copper (9.3 µg/L limit in water with 100 mg/L hardness); 1,290 µg/L of lead (3.2 µg/L limit in water with 100 mg/L hardness). Spreadsheet data is attached as Exhibit 9.
[40] E. Evarts, Area Fisheries Supervisor, DNR Request for Comments - Dam Safety - Construction - St. Louis County - Applications 2016-1383 and 2016-1380, June 19, 2017, attached as Exhibit 10.

DNR regulators have yet to require PolyMet to analyze and disclose the chemical parameters of the metals processing and other wastes the company proposes to store in the HRF. Despite plausible dam failure scenarios highlighted by its consultants and concerns of its own managers about the impacts of HRF waste release on water quality, the DNR has not required PolyMet to analyze and disclose the downstream impacts to water qualities, fisheries and public health in the event of dam failure at PolyMet's proposed HRF waste facility. As noted by WaterLegacy and others who commented on the FEIS, PolyMet's analysis and disclosures related to the HRF are long overdue. The DNR has a legal and fiduciary obligation to require PolyMet's rigor and transparency.

Inadequate Dam Stability Analysis
In addition to declining to analyze the potential hazards of HRF dam failure, PolyMet's HRF dam permit documents contain self-serving assumptions and omissions that minimize and avoid assessment of the threat of dam failure.

Although the EPA has specifically requested that PolyMet perform a liquefaction analysis for the HRF,[41] PolyMet has instead assumed that the HRF waste fill is not subject to liquefaction,[42] without specifying any properties of the underlying foundation or dam perimeter materials that would support, let alone guarantee, the validity of this assertion.[43] PolyMet's HRF wastes are liquid wastes. Even after closure, it may take years for dewatering and stability of the wastes to be attained. In fact, during closure "access to the Residue surface may be somewhat difficult, due to the fine-grained characteristics of the Residue" and the "Residue, consisting of saturated silt-size particles, would be difficult to regrade to steeper slopes as part of closure."[44]

HRF wastes would be silt-sized particles, composed of 84% silt, 15% sand and 1% clay.[45] A blanket assumption that silt materials like the HRF residues are not subject to liquefaction is unreasonable. As explained in a recent international review, "A plethora of case histories evidence that silt having low clay content is highly sensitive to liquefaction."[46] This risk could be posed long after closure should water infiltrate the HRF.

PolyMet's claims that the assumptions made for its stress-deformation analysis at closure are "conservative," but they are not. PolyMet assumes that waste residues are homogenous, that foundation settlement is complete, that there is no infiltration due to precipitation, and that pore water pressure will approach zero pounds per square foot during dewatering.[47] Infiltration, incomplete settling and non-homogeneous wastes could increase deformation stress. And achieving zero pore water pressure would require malfunction-free drainage and "hydraulic conductivity of the consolidated residue" that isn't "lower than expected."[48]

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[41] EPA PolyMet SDEIS Comments Mar. 13, 2014, p. 16 of Attachment B to WaterLegacy Letter to U.S. Army Corps June 29, 2017, attached with these comments as Exhibit 11.
[42] HRF Geotech., p. 23.
[43] *Id.*, p. 12. HRF dams would be constructed from soil borrow and bulk tailings. HRF Permit Application, p. 7.
[44] HRF Mgt. Plan., p. 33.
[45] HRF Geotech., p. 23.
[46] D. Singh *et al*., Liquefaction Susceptibility of Silty Soils, *Int'l J. of Advances in Sci. Eng. And Tech*., Vol-5, Iss-1, Jan. 2017, attached as Exhibit 12.
[47] HRF Geotech, p. 36.
[48] *Id*., at 37.

Finally, although geologists recognize that, when a fault is inferred by the Minnesota Geological Survey, it means that the fault is present, PolyMet continues to insist that the fault beneath the proposed HRF facility may not exist.[49] PolyMet then assumes that the HRF drainage system will suffice to relieve any excess power water pressure that could develop along the fault.[50]

Although extensive blasting will be required at the edge of the HRF facility to break apart rock outcroppings, with "the potential to cause pore water spikes and permanent deformation," "tension cracks" in the HRF, and cumulative permanent deformation,[51] PolyMet suggests that analysis of the risk of deformation from blasting be deferred until some later day after permits have been issued and HRF construction is underway. "The potential blasting configuration for the construction of the HRF and its effect on the inferred fault is beyond the scope of this document."[52]

On September 15, 2017, the DNR released the draft PolyMet HRF dam safety permit to the public. PolyMet's HRF dam permit application contained no analysis of the potential hazards of dam failure, no characterization of the toxicity of wastes to be contained by the proposed HRF dam, and a self-serving set of assumptions to minimize the risks of residue liquefaction and stress deformation of liners beneath the HRF. Testing or specification for the properties of HRF wastes remained incomplete, and PolyMet admitted that effects of HRF waste liquefaction, precipitation infiltration, pore water pressure along the HRF fault, or deformation from blasting were beyond the scope of HRF dam safety analysis. The HRF Geotechnical Data Package used for PolyMet's 2016 HRF dam safety application didn't even incorporate results of PolyMet's 2014 geotechnical investigations.[53] PolyMet's HRF dam safety permit application was and continues to be woefully incomplete.

WaterLegacy has learned that on September 26, 2017, after the HRF draft dam permit was released, Gale-Tec Engineering detailed to DNR's consulting engineers at EOR steps that would now be taken to analyze HRF liner deformation due to regulatory concerns. Their letter read:

> We understand that the MPCA and MnDNR are currently reviewing the Polymet Dam Safety Permit and Permit to Mine and have expressed concerns about the design of the Hydromet. Residue Facility, which has been proposed to be constructed within a low area the previously served as the LTVSMC Emergency Discharge Basin. The permitting agencies are concerned about potential different settlement caused by the basin construction and potential distress to the double composite liner system that has been proposed to unlay the facility and minimize the potential for environmental contamination.[54]

This engineering review will be helpful, but it is not sufficient.

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[49] *Id.*, at 39. For discussion of MGS inferred faults at the FTB and HRF, see expert review of J. D. Lehr (2014), pp. 14-15, provided to DNR in Appendix to WaterLegacy's FEIS Comments, referenced in footnote 5.
[50] HRF Geotech., p. 39.
[51] *Id.*, 48-49.
[52] *Id.*, at 49.
[53] *Id.*, at 12.
[54] S.M. Gale and N.M. Lichty, Letter to C. Olivier, Proposal for Geotechnical Engineering Review of Polymet Hydromet. Residue Facility Foundation Design, Sept. 26, 2017, attached as Exhibit 13.

Since the draft environmental impact statement in 2010, the DNR has allowed PolyMet to proceed with plans for its flotation tailings basin and hydrometallurgical residue facility with inadequate geotechnical information, incomplete chemical characterization of wastes, deficient analysis of potential dam failure hazards, misleading and self-serving assumptions, dismissal without analysis of mitigation alternatives, and incomplete and continually changing presentation of proposed designs.[55] In the draft EIS, supplemental draft EIS and final EIS, it was represented to the public that complete data and engineering design would be available before permitting.[56] That day has arrived, but the appropriate research, specificity and transparency have not.

It is long past time for the DNR to require PolyMet to produce the necessary data, final design and analysis described in these comments and identified by its engineers and consultants. Draft dam safety permits must be deferred or denied until that date finally arrives.

2. <u>Inadequate Regulation and Incomplete Design in Draft PolyMet Dam Permits</u>

Minnesota has no experience with copper-nickel mining wastes and little experience with dams that serve as a closed system, collecting all surface drainage and seepage and returning it to the waste contained by the dam.[57] When the Minnesota Pollution Control Agency (MPCA) required that surface runoff and leachate be collected and pumped back to the top of an LTV Steel Mining Company coal ash heap at Taconite Harbor, the wastes liquefied and collapsed.[58] The modest level of pumping from surface seep collection systems back into the LTVSMC basin has increased the phreatic surface,[59] a factor that increases dam failure risk.

Historic DNR dam safety permits provide an insufficient and inadequately protective blueprint for permits that would prevent dam failure and potential water quality, health and environmental hazards at the proposed PolyMet FTB and HRF, both of which propose to permanently contain sulfide mine wastes. WaterLegacy believes that it is highly likely that neither the proposed PolyMet FTB dam nor the proposed PolyMet HRF dam can be permitted consistent with protecting dam stability and water quality. The location of the proposed FTB tailings on top of the existing LTVSMC tailings basin precludes the stability of liners needed for dry stack tailings. Designs proposed for the PolyMet FTB waste facility are unlikely to meet both the requirements for dam safety and pollution control through subaqueous disposal, if they can meet either.

The location of the proposed HRF waste storage is unsuitable for a facility storing highly concentrated and toxic liquid wastes, even if it might be demonstrated at some point that they are not "hazardous" under RCRA. Even solid waste facilities cannot be located on top of wetlands and unsuitable soils upstream of drinking water supplies. PolyMet's lack of experience and the paucity of detail provided in the documents supporting its application for the HRF dam permit should indicate to any conscientious regulator that permitting this facility is not a risk worth taking.

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[55] *See* WaterLegacy comments to U.S. Army Corps of Engineers and exhibits, June 29, 2017, *supra*, Exhibit 11.
[56] *See e.g.*, PolyMet FEIS 2-12, 3-15, 3-118, 3-140, 5-179, 5-201, 5-657.
[57] Although the 1981 Dam Safety permit to the Erie Mining Co. for the North East Extension of its taconite tailings basin, permit 81-2000, attached as Exhibit 14, proposed a closed system for seepage or treatment of any waters released in paragraph XIX, that permit condition was never enforced.
[58] *See Arrowhead Electric Coop. v. LTV Steel Mining Company*, 568 N.W. 2d 875 (Minn. App. 1997).
[59] FTB Geotech, p. 14.

Minnesota state agencies may not be ready yet to conclude that neither PolyMet's proposed FTB dam nor its HRF dam would provide adequate protection against potential hazards to public health, safety, welfare and the environment. However, we trust that Minnesota state regulators believe that, before that decision is made, any PolyMet sulfide mine dam permits under review must be specific and enforceable, and must reflect final designs. Minn. R. 6114.0410, Subp. 6.

The draft PolyMet dam permits for both the FTB and the HRF are insufficiently specific and enforceable. They defer questions of materials testing, design, construction, operations, closure and long-term maintenance. They reflect incomplete designs, even as to the most fundamental features of dam construction. They fail to provide enforceable safety requirements, to assure compliance with conditions for dam safety, or to require that adverse findings will trigger protective contingencies. They fail to define the wastes that the dams would contain or to provide the level of detail on long-term maintenance, monitoring and inspections required to determine financial assurance. The omissions and deficiencies noted below are suggestive; they are not an exhaustive list of our concerns regarding the draft PolyMet dam permits.

A. Flotation Tailings Basin (FTB) Draft Dam Safety Permit (2016-1380)

Materials Testing: These comments have previously described deficiencies in testing of LTVSMC tailings and PolyMet flotation tailings. The stability of the FTB dam rests on properties of these materials. Permit conditions should ensure FTB dam stability by requiring that PolyMet demonstrate specific properties of LTVSMC tailings, such as a minimum undrained shear strength, and attainment of factors of safety under all scenarios. Although the draft PolyMet FTB dam permit requires additional testing of LTVSMC tailings, it contain no specific materials or safety factor requirements and provides no criteria for the DNR to disapprove testing or delay construction.[60]

Permit conditions should similarly ensure stability by precluding dam construction until updated pilot testing of PolyMet tailings confirms specific modeled properties. The FTB permit should then require that, immediately upon the start of processing, tests of flotation tailings must demonstrate the specific properties upon which PolyMet's models relied for performance and all factors of safety must be met. Findings that flotation tailings have less favorable material properties than prescribed should trigger specific design changes that reduce the risk of dam failure. However, the draft PolyMet FTB dam permit requires no additional pilot testing before construction, contains no materials or safety factor requirements, and provide no consequences other than a reporting requirement if properties of flotation tailings are different from those "expected" by PolyMet.[61]

Capacity: PolyMet has stated that its copper-nickel mine project will generate approximately 11.27 million short tons of flotation tailings annually (approximately 10,000,000 in-place cubic yards annually) and that the tailings waste facility it has proposed and modeled has the capacity to store tailings for 20 years of operation.[62] Permit conditions should limit the tailings capacity for which the PolyMet FTB dam is approved and restrict the permit's application to PolyMet's

[60] FTB Draft Dam Permit, ¶29.
[61] *Id.*, ¶41.
[62] FTB Mgt. Plan, p. 2.

flotation tailings to avoid use of the dam beyond its intended purpose. The draft PolyMet FTB dam permit contains no limits on the volume or type of tailings to be stored behind its dams.

Factors of Safety: The final section of these comments argues that PolyMet's proposed factors of safety for the FTB dam are not sufficiently protective. Or Once an appropriate level of safety is set, permit conditions should specify minimum factors of safety applicable to drained, undrained and liquefaction scenarios and require periodic modeling of factors of safety based on dam conditions. Permit conditions should trigger immediate action, potentially limiting processing as well as changing dam operations, should modeled factors of safety fail to meet minimum standards or drop by more than a trivial percentage. The PolyMet draft FTB dam permit neither specifies a minimum factor of safety nor ensures, given the many uncertainties in PolyMet's analysis, that the dam as constructed will meet expected safety levels.

Dam & Buttress Construction: PolyMet has admitted that excavation of bulk tailings for use in FTB dam construction, even if they are "mostly" LTVSMC coarse tailings, will contain "inclusions of LTVSMC fine tailings and a small amount of slimes."[63] Permit conditions should preclude inclusion of slimes and fines in dam construction materials and require that rock fill or other suitable materials be used for dam construction should LTVSMC tailings fail to meet this requirement. The draft PolyMet FTB dam permit does not discuss the properties of materials that will be used in dam construction.

DNR's consulting engineers have recommended complete removal of peat deposits near the toe of the existing tailings basin dam so that the new PolyMet dam buttress would have a solid footing.[64] Documents supporting PolyMet's application for an FTB dam permit state that various dam cross-sections require a buttress to achieve a 1.1 minimum factor of safety.[65] In the case of Cross-Section N on the south side of the tailings waste basin adjacent to Second Creek, for example, a blanket buttress almost 400 feet wide would be required to meet even a 1.1 minimum factor of safety.[66] Permit conditions should require the complete removal of peat soils prior to buttress construction and specify design requirements for buttresses to meet factors of safety under worst-case liquefaction conditions. The draft PolyMet dam permit requires written approval of plans from the DNR prior to buttress construction, but does not require specific measures, such as peat removal, or state the design requirements or minimum safety factors required for dam construction.[67]

Beach and Freeboard: DNR's consulting engineers commented that FTB dam stability analysis was based on maintaining a beach length of 625 feet to minimize the risk of erosion at the edge of the basin and that some of PolyMet's models did not seem to correctly account for a potential rise in water levels.[68] The draft PolyMet FTB dam permit sets a clear requirement that the permittee "maintain a normal beach length of at least 625 feet and a normal freeboard of at least 9 feet." However, this condition should be clarified to require: 1) that the permittee immediately inform DNR when beach and freeboard requirements are less than the permitted values; 2) that

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[63] FTB Geotech., p. 39.
[64] EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, p. 4.
[65] FTB Geotech., p. 111.
[66] *Id.*, pp. 93, 111.
[67] FTB Draft Dam Permit, ¶30.
[68] EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, p. 4.

the permittee, rather than some unspecified party must undertake corrective actions; and 3) the nature of steps that must be taken to restore these parameters as quickly as feasible.[69]

Bentonite and Dry Closure: As discussed in more detail in the final section of these comments, DNR staff and consulting engineers have serious concerns about the performance of bentonite to prevent water infiltrating the FTB dam and about the risk that bentonite will increase slope erosion. They have also questioned the stability and long-term maintenance of the FTB with wet ponding, as opposed to dry closure. Before a FTB dam permit can be considered, let alone approved, final evaluations must be completed and decisions made as to which, if any, designs will ensure dam safety and water pollution control. Permit conditions must then specify the mitigation design to be used, the specifications it must attain, and the contingencies that would be triggered if specifications are not met.

The draft PolyMet FTB dam permit makes no decision on the use of bentonite. It defers the question of whether bentonite is a suitable mitigation design to unspecified pilot/field tests prior to construction. Even then, the draft permit fails to specify how pilot/field tests must be done, the findings they must demonstrate, or the consequences for design and permitting if such findings cannot be made.[70] With respect to dry closure, the draft PolyMet FTB permit kicks the can even farther out into the future. The draft dam permit proposes that PolyMet construct its dam, fill the flotation tailings basin with hundreds of millions of tons of tailings waste and, only then, explore and submit updated "future closure options, such as a dry cap or other technologies that may improve closure conditions."[71] This permitting approach does not comply with law.

Dam Operations and Perpetual Maintenance: Dam operation, maintenance, inspection and monitoring, whether to control water levels, repair erosion or maintain the drainage and pumping system, can be determinative of dam safety. This concern is elevated once processing operations cease. PolyMet's Contingency Action Plan only specifies protections while operations are ongoing:

> During operations, personnel will be on-site 24 hours a day, 7 days per week. Personnel will therefore be able to review conditions and monitor for changing conditions. Additionally, monitoring instrumentation is planned to be automated by a remote monitoring system, which includes thresholds and automated alarms data trends toward or falls outside of pre-established thresholds.[72]

Post-closure, PolyMet only proposes an annual inspection of vegetation and erosion repair, snow removal during winter to allow access, and reconstruction of eroded dam crest, slope or toe – presumably when found during an annual inspection.[73]

DNR staff engineers and consulting engineers have questioned PolyMet's understanding of necessary maintenance tasks post-closure. EOR and Spectrum Engineering have emphasized perpetual maintenance of PolyMet's FTM dam design will require "perpetual operation,

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[69] FTB Draft Dam Permit, ¶48.
[70] FTB Draft Dam Permit, ¶31.
[71] FTB Draft Dam Permit, ¶45-46.
[72] Contingency Action Plan for the Flotation Tailings Basin, May 15, 2017, p. 13 in Attachment F to the FTB Mgt. Plan.
[73] FTB Mgt. Plan, p. 41.

maintenance, and capital replacement of the pumping system to maintain appropriate tailings water levels (pumping in or pumping out)," "major capital improvements like bentonite re-application (say every 10-20 years)," structural issues, monitoring, and a third party dam safety consultant, in addition to maintenance costs for regular erosion repair, tree/vegetation replacement and regrading.[74] Managing the water level, in particular, would be needed to prevent pond overflow or drying out and oxidizing of tailings.[75]

Permit conditions should incorporate a detailed and prescriptive written Operation, Maintenance and Inspection Plan that addresses operations, closure and post-closure perpetual maintenance. Post-closure and perpetual maintenance should be detailed to include contingency action in the event of dam failure, remote monitoring, on-site inspection at spring melt and during heavy precipitation events as well as frequent inspections, management of water levels, periodic capital improvements, and structural repair of erosion, as well as maintenance of vegetation.

The PolyMet draft FTB dam permit would allow PolyMet to propose an Operations and Maintenance Plan for DNR approval without public review – long after permitting is complete and financial assurance is set. No content requirements are specified for the Plan, which could be changed by DNR without a permit amendment.[76] The draft FTB dam permit would require PolyMet to "maintain the dimensions and elevations of the dam as described herein" but does not actually describe the dimensions or elevations that must be maintained.[77] Although the draft FTB dam permit requires "perpetual maintenance" of the integrity of the tailings basin, no permit condition specifies that maintenance requires water management, capital replacement of the pumping system, periodic investment for bentonite replacement, erosion repair, monitoring, inspections, third party safety evaluation, or vegetation management.[78]

Observational Method: The draft PolyMet FTB dam permit proposes the "Observational Method" to give the permittee the "flexibility to modify the design as new information is obtained during the multi-year construction of the tailings basin dam," and states that "changes in the design, construction, operation or maintenance of the facilities authorized by this permit" at the "sole discretion of the DNR."[79] WaterLegacy is concerned that this version of an "Observational Method" undermines the permitting process and the opportunity for public review. In addition, as the preceding discussion has detailed, the PolyMet FTB tailings design and draft permit are inadequate to support an observational approach:

> "The EOR Review Team agrees that the Observational Method can and should be used during construction, but it is not a substitute for careful initial design. The EOR Team concluded that the permit application lacks the detail and description of contingencies for the Observational Method to be effective. If monitoring data indicate a potentially unsafe condition during construction, then the alternate construction methods and designs (contingencies) must be already in place so that they can be implemented immediately."[80]

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[74] Emails, Spectrum Engineering, EOR & DNR, PolyMet Tailings Dam Comments Appendix 6, May 31-June 1, 2017, attached as Exhibit 15.
[75] *Id.*
[76] FTB Draft Dam Permit, ¶33-34.
[77] *Id.*, ¶34.
[78] *Id.*, ¶47.
[79] *Id.*, ¶ 36.
[80] EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, p. 3

B. Hydrometallurgical Residue Facility Draft Dam Safety Permit (2016-1383)

Characterization of HRF Storage Materials: As explained in the first section of these comments, the chemical parameters of proposed PolyMet hydrometallurgical residue waste have yet to be characterized and disclosed to regulators and the public. The record is unclear whether PolyMet will deposit other materials, such as coal ash and sludge from treatment facilities, along with nickel processing HRF wastes. Yet, even the consideration of permitting for the HRF dam is contingent on the supposition that the wastes to be contained by the dam will not be hazardous.[81] Permit conditions must specify: 1) that wastes to be contained by the HRF dams shall not be hazardous, as defined under Minnesota laws,[82] whether singly or in combination; 2) the specific waste streams that may be deposited in the HRF; 3) the testing that PolyMet must supply to the DNR, the MPCA and the public demonstrating that wastes are not hazardous prior to depositing them in the HRF; and 4) that if any wastes are found to be hazardous whether prior to or subsequent to deposit in the HRF, they must be removed from the site and deposited in a licensed hazardous waste facility. The draft PolyMet HRF dam permit contains no conditions at all as to the nature, composition or testing of HRF wastes.

Foundation: The first and final sections of these comments detail broad concerns regarding the unsuitable foundation beneath PolyMet's proposed hydrometallurgical residue facility. If permitting the HRF is even to be considered, permit conditions should explicitly require the removal of all wetlands and soft soils from the HRF site and the establishment of a sound foundation prior to construction. The draft PolyMet HRF dam permit neither requires removal, rejects the "foundation preload" proposed by PolyMet, sets any specific standards for what PolyMet must "confirm" in order to move forward with its preferred and less expensive plan for the HRF foundation, nor even sets a timeframe for decisions.[83] The most basic determinations on standards and design for the HRF foundation would be indefinitely deferred with no substantive requirements.

Dam construction: PolyMet's HRF dam permit application and supporting materials provide little specificity regarding dam construction. PolyMet's application states that HRF perimeter dams will be constructed using soil borrow and bulk tailings selected from locations at PolyMet's discretion.[84] The perimeter dams may "possibly" also include quarried rock.[85] Permit conditions should state where quarried rock construction is required and specify the materials, dimensions and properties of all dam construction materials. The draft HRF dam permit notes that MPCA must approve dam designs since the HRF would store liquid waste.[86] However, the draft permit provides no specifications for dam construction materials or dam design, other than to say that changes in HRF designs must be reported to the DNR in an annual report.[87]

The draft HRF dam permit requires an unusual level of detail in the annual report PolyMet must submit to DNR, including HRF photographs, graphical presentations of instrumentation

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[81] *See e.g.* HRF Mgt. Plan, p. 6.
[82] See Minn. Stat. §116.06, Subd. 11 for the definition of hazardous wastes.
[83] HRF Draft Dam Permit, ¶ 25-26.
[84] HRF Permit Application, p. 7, Table 3-2.
[85] HRF Mgt. Plan, p. 7.
[86] HRF Draft Dam Permit, ¶45.
[87] *Id.*, ¶33.

"including but not limited to data from pond level monitors, piezometers, inclinometers, extensiometers, and settlement plates at the HRF," and a brief discussion of any monitoring results that "appear to be irregular or out of tolerance."[88] Rather than serving as reassurance, this condition suggests that no standards for regularity or tolerance have been set, and that the likely performance and even the appearance of the HRF are quite uncertain.

Freeboard and Water Management: The HRF would be located adjacent to the FTB waste facility, so precipitation and snow melt conditions would be the same. The HRF, unlike the FTB facility, seems to have no emergency overflow mechanism to prevent overtopping or dam failure during a massive precipitation event or in the event of disruption or blockage of the return water pipeline.[89] Permit conditions should specify emergency water management contingencies for the HRF and require that the HRF maintain at least a 9-foot freeboard as well as an appropriate beach.[90] The draft PolyMet HRF dam permit proposes a freeboard of only 6 feet, no beach, and no mechanism to correct abnormal conditions that reduce freeboard below the permitted value.[91]

Blasting: Concerns about the impacts of blasting at the HRF on the underlying fault and the risk of liner deformation are discussed in the first section of these comments. Permit conditions should require that all blasting to loosen, break or reshape HRF rock outcroppings must be done prior to construction of the HRF dam, and that effects of blasting on the existing fault and cracks that might affect dam stability must be analyzed and repaired before HRF dam liners are installed or HRF wastes deposited. The draft PolyMet dam permit does not mention blasting or the fault beneath the HRF and does not address this source of cumulative deformation.

Factors of Safety: The HRF dam would contain liquid wastes, the dam perimeter would be constructed of soil and tailings, and the foundation beneath HRF dam liners may be compacted wetlands, soft soils and tailings concentrates. Permit conditions should specify the factors of safety required for HRF dam slope stability and that these factors of safety must be computed under worst-case liquefied conditions and using project-specific shear testing.[92] The draft PolyMet HRF dam permit neither requires factors of safety nor specifies how attainment of safety factors should be calculated.

Dam Operations and Perpetual Maintenance: The proposed PolyMet HRF dam will require perpetual monitoring and maintenance. The accumulation of solids in the return water pumping system will require continual monitoring and maintenance to prevent clogs with suspended particles.[93] Inspections will also be needed to observe evidence of "dam structure deformation (e.g., slope bulging or crest settlement)," evidence of "leakage, overland runoff or erosion" and possible evidence of "piping/subsurface erosion downstream of the dam."[94] After closure, there is a potential for "clogging, blockage, or damage" to the closure inlet box, because pipes are

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[88] *Id.*
[89] *See* HRF Dam Break Analysis, *supra*, pp. 2-3.
[90] Freeboard of 6 feet required in FTB Draft Dam Permit, ¶48. Beach length is referenced in HRF Draft Dam Permit, ¶ 31 as part of a future Operations Plan, but none is required as a permit condition.
[91] HRF Draft Dam Permit, ¶44. Supporting documents also describe no mitigation design to address overflow.
[92] HRF general slope stability results reported by PolyMet appear to consider only drained shear strengths. Infinite slope stability results are based on "commonly reported" data, not project-specific shear testing. HRF Geotech., pp. 46, 48.
[93] HRF Mgt. Plan, p 21.
[94] *Id.*, p. 25.

through embankments in closure.[95] Without insulation, any break or disruption could lead to a frozen water return pipeline.[96]

Documents provided by PolyMet to support its application for an HRF dam permit propose that the HRF will be inspected daily and weekly during operations and that monitoring points will be surveyed twice per year to determine horizontal and vertical deformation of the HRF dams.[97] However, PolyMet's plan for HRF maintenance is meager and short-lived:

> The frequency of monitoring will decrease and monitoring will eventually cease once the cover system has been completed, once vegetation has become established, and once it is confirmed that there are no areas where surface runoff is becoming channelized and causing erosion of the facility dams.[98]

Permit conditions for the HRF dam should incorporate a prescriptive written Operation, Maintenance and Inspection Plan that addresses operations, closure and post-closure perpetual maintenance, including residue spigotting, water management, redundant piping systems, emergency contingencies, and geotechnical specifications and monitoring requirements. Permit conditions should specify requirements at closure and post-closure to demonstrate structural integrity, properties of materials after dewatering, the means and efficacy of sealing the HRF from water infiltration, and the level to which liner leakage must be limited. HRF permit conditions should also provide for perpetual inspections and maintenance, including surveys for deformation, testing for infiltration and leaks. HRF permit conditions should detail the triggers and contingent actions, ranging from repairs to excavation of wastes, in the event leaks or containment failures during operations, closure or post-closure threaten public health, safety, welfare and the environment.

The PolyMet draft HRF permit would allow PolyMet to submit its Operation, Maintenance and Inspection Plan for DNR approval without public review – long after permitting is complete and financial assurance is set in the permit to mine.[99] Although the topics for the Plan are set forth, the permit sets no standards that the Plan must meet and provides no basis for DNR's approval or denial of the Plan.[100] The draft HRF permit requires a permit amendment for any repair that would "change the hydraulic capacity or structural character of the dam," but the permit contains no conditions for either the hydraulic capacity or structural character of the dam.[101]

Under the draft HRF permit, PolyMet would not submit a closure plan until 2 years before the end of planned operations; and no conditions are specified that must be met at closure.[102] The draft HRF permit states that the DNR Commissioner may set requirements to ensure that the permittee "will remain financially responsible for carrying out the activities required for perpetual maintenance, and that adequate funding for perpetual maintenance continues to

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[95] B. Johnson, DNR, NorthMet Project Geotech/Hydromet Mgt. Plans, July 5, 2016, attached as Exhibit 16.
[96] *Id.*
[97] HRF Mgt. Plan, pp. 25, 28.
[98] *Id.*, p. 36.
[99] HRF Draft Dam Permit, ¶ 31.
[100] *Id.*
[101] *Id.*, ¶32
[102] *Id.*, ¶ 42.

exist."[103] However, it lacks requirements for closure and perpetual maintenance of the HRF that could be used to determine financial assurance in the permit to mine.

Draft Dam Safety permits for the PolyMet FTB and HRF fail to meet legal requirements for final design submittal, reasonableness, or regulation to protect public health, safety, welfare and the environment. They must be rejected.

3. Failure to Protect Public Health, Safety, Welfare and the Environment

Draft PolyMet FTB and HRF dam permits, along with their supporting documents, fail in several important requests to address concerns raised or even to follow recommendations of the DNR's own senior staff engineers and consulting engineers. As reflected throughout these comments, WaterLegacy believes that investigations must be required, risks must be analyzed, standards must be specified, designs must be finalized and alternatives must be required to protect public health, safety, welfare and the environment. Even in the face of PolyMet's resistance, the DNR must require protective factors of safety, designs, technologies and practices that ensure dam stability and water quality. If for this particular project and proposed waste disposal locations, no mitigation alternatives can achieve this dual requirement, the DNR must be prepared to deny PolyMet dam safety permits.

A. Factors of Safety

Prior sections of these comments have raised concerns about PolyMet's failure to conduct a thorough dam stability analysis of the HRF and about the lack of specificity in the draft FTB and HRF dam permits as to the factors of safety applicable to PolyMet's dams. DNR documents reflect that the selection of factors of safety for the PolyMet dams has been contentious. In 2010, when PolyMet proposed a safety factor of 1.05, the U.S. Environmental Protection Agency recommended that DNR use a safety factor of 1.5:

> EPA's principle concern with this work relates to the factors of safety used to design the new tailings pond. . . *Steve Hoffman was asked about observations at other sites, and noted that the industry standard, driven by companies, is generally is migrating to a safety factor of 1.50.*[104]

After several months of internal discussion, DNR's senior dam safety engineer concluded:

> DNR should accept the 1.20 value as the acceptable Factor of Safety for Liquefaction (F_{Liq}). This is the recommended value from the MSHA "2009 Engineering and Design Manual, Coal Refuse Disposal Facilities" (EDM). There are several additional sources that recommend the 1.20 value, including internal DOW Dam Safety guidance documents. This F_{Liq} should be applicable for both seismic events and pore water pressure.[105]

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[103] *Id.*, ¶ 43.
[104] Review and Conference Call Record, EPA review of NorthMet Project Flotation Management Plan (FTMP), Nov. 29, 2010, p. 3, attached as Exhibit 17.
[105] DNR Memo, Dana's recommended direction on PolyMet, Feb. 23, 2011, attached as Exhibit 18.

The Co-Lead Agencies agreed in May 2011 that the factor of safety should meet or exceed 1.50 for drained strength, 1.30 for undrained non-liquefiable materials and 1.20 for static as well as seismic liquefaction.[106] PolyMet was not "receptive" to performing a safety analysis for the FTB for the case where full liquefaction would be triggered.[107]

Recently, the Federal Energy Regulatory Commission (FERC) set Safety Guidelines for dam engineering. For dams with either a high (Class I) or significant (Class II) hazard potential, FERC recommended a minimum factor of safety of 3.0 under usual loading conditions, 2.0 under unusual loading conditions and 1.3 for seismic liquefaction conditions after an earthquake.[108] Even if cohesion is not relied on for dam stability, FERC recommended a minimum factor of safety of 1.5 in the worst static case and 1.3 for seismic liquefaction post earthquake.[109]

WaterLegacy believes that factors of safety for both the FTB and HRF dams must be reviewed and updated to apply current protective standards, increasing the factors of safety for proposed PolyMet sulfide mine waste dams.

Even applying a 1.10 factor of safety for liquefied conditions, which falls below the recommendation of DNR's senior engineer as well as below FERC safety guidelines, PolyMet's proposed FTB does not meet this minimum safety factor. Under liquefied conditions triggered by erosion, the calculated factor of safety at the FTM dam is 1.07, which is below the 1.10 minimum safety level prescribed for the PolyMet FTB.[110] We don't know how likely it is that erosion would trigger liquefaction, although this is one of the scenarios with which DNR's consulting engineers are concerned. However, should this trigger occur, there is nearly a 1 in 50 chance that the FTB dam would fail.[111]

DNR must set an more protective factor of safety for the FTB and HRF dams, particularly in the case of static liquefaction, require that PolyMet thoroughly and candidly evaluate compliance with this new safety factor and preclude further permitting activity unless and until dam designs meet or exceed all applicable factors of safety.

B. FTB Dry Tailings Designs & Closure Plans

WaterLegacy's comments on the PolyMet FEIS, along with attached exhibits and expert opinions, have expressed concern about the proposed storage of wet slurry tailings at the PolyMet FTB, particularly in light of the catastrophic failures of the Mount Polley dam in British Columbia, Canada and the Fundão Dam in Samarco, Brazil.[112] A panel of experts analyzed the cause of the Mount Polley tailings impoundment failure and made the following key recommendation in their Independent Report:

> [T]he future requires not only an improved adoption of best applicable practices (BAP), but also a migration to best available technology (BAT). Examples of BAT are filtered,

[106] Geotechnical Stability IAP Summary Memo NorthMet Project EIS, May 18, 2011, p. 1, attached as Exhibit 19.
[107] T. Radue. Barr Eng., Email to DNR, PolyMet Follow-Up, Jan. 14, 2013, attached as Exhibit 20.
[108] FERC, Hydropower Safety Guidelines Engineering Guide, Ch. III, p. 3-26, Mar. 4, 2016, attached as Exhibit 21.
[109] *Id.*, p. 3-27.
[110] FTB Geotech, pp. 109, 117.
[111] *Id.*, p. 114.
[112] WaterLegacy's FEIS Comments, pp. 69-72, 84-86, incorporated by reference in footnote 5.

> unsaturated, compacted tailings and reduction in the use of water covers in a closure setting.[113]

The *Mount Polley Independent Report* explained the "intrinsic hazards associated with dual-purpose impoundments storing both water and tailings" and stated, "BAT has three components that derive from first principles of soil mechanics: 1. Eliminate surface water from the impoundment. 2. Promote unsaturated conditions in the tailings with drainage provisions. 3. Achieve dilatant conditions throughout the tailings deposit by compaction."[114]

This analysis is now widely shared within the industry. A summary article from the 2017 annual meeting of the International Commission on Large Dams (ICOLD) concluded:

> One possible measure includes reduction of pore water from the tailings mass, which can improve the rheological characteristics so that the stored tailings solids are non-flowable as described by Adams et al (2017). . . For each of the presented case studies, it was the large volume of water in the TSF that exaggerated the downstream inundation extent. In the recent Mount Polley tailings dam breach incident, it has been acknowledged that the foundation failure of the dam would have resulted in a dam crest deformation and potentially some tailings slumping, but not in a catastrophic breach and release of the stored TSF content.[115]

Others have simplified, "[T]he presence of large quantities of stored water is the primary factor contributing to most of the recent tailings storage failures. The risk of physical instability for a conventional tailings facility can be reduced by having good drainage and little (if any) ponded water. Simply put, 'no water, no problem.' "[116]

Minnesota rules for non-ferrous mining also require elimination of substantially all water in tailings, particularly at closure. A reactive mine waste storage facility[117] must be designed either to modify or store wastes so that they are no longer reactive or "during construction to the extent practicable, and at closure, permanently prevent substantially all water from moving through or over the mine waste." Minn. R. 6132.2200, Subp. 2, Item B.

DNR's consultants and staff engineers have expressed reservations about PolyMet's current plans to maintain a pond at the top of the flotation tailings storage facility. The EOR review team concluded, "Dry closure (no water ponding) requires a greater initial investment, but has much lower ongoing maintenance costs and less long-term environmental risk."[118] DNR's senior

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[113] Independent Expert Engineering Investigation and Review Panel, *Report on Mount Polley Tailings Storage Facility Breach,* Jan. 30, 2015, p. iv, provided as Exhibit 25 to WaterLegacy FEIS Comments, *supra*. Online at https://www.mountpolleyreviewpanel.ca/sites/default/files/report/ReportonMountPolleyTailingsStorageFacilityBreach.pdf
[114] *Id*., p. 121.
[115] Martin et al., Challenges with conducting tailings dam breach assessments, 85th Annual Meeting International Commission on Large Dams (ICOLD), July 3-7, 2017, *supra*, Exhibit 7.
[116] Water Management Considerations for Conventional Storage, http://www.tailings.info/technical/water.htm, last visited on Oct. 15, 2017.
[117] "Reactive mine waste" is defined as waste that is "shown through characterization studies to release substances that adversely impact natural resources." Minn. R. 6132.0100, Subp. 28. Sulfates in tailings waste and metals, such as nickel, that leach from tailings even under circumneutral conditions, would adversely impact natural resources.
[118] EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, p. 5

dam safety engineer explained the reason dry closure was recommended for the PolyMet FTB; "The geomorphological issues are essentially why I favor dry closure."[119]

Consulting engineers at EOR and Spectrum Engineering agree that PolyMet's plan to seal the FTB embankment with bentonite would be geomorphologically unstable.[120] Donald Sutton, who previously identified the bentonite seal a "hail Mary type of concept" that "will exacerbate erosion and slope failure and will eventually fail,"[121] explained in a May 31, 2017 email to EOR and DNR the risks of catastrophic dam failure and tailings release under PolyMet's current plan:

> The stair step FTB embankment sealed with bentonite is geomorphologically unstable and will erode, potentially cutting back into the pooled water, releasing the water and saturated tailings. Initially, surface water will collect in the horizontal ditch/ponds along the toes of lifts 1 and 5, and infiltrate into the embankment via the underdrain and the coarse LTV tailings beneath lift 1. Later, after the bentonite soil erodes from the slopes, the ditches will fill, plugging the underdrain, forcing the water to overflow the bench and cause head cutting in the non-cohesive tailings. If the FTB is to remain as a permanent structure without perpetual maintenance, then I recommend that the embankments be designed using established geomorphologic land reclamation principals. Otherwise there is a high probability that the embankments will eventually fail due to erosion, and catastrophically release the saturated tailings.[122]

The PolyMet FEIS relied on the plan for bentonite amendment of the pond on top of the tailings and of the exposed beach areas of the dam to claim that there would be a barrier limiting oxygen diffusion into the tailings and oxidation of sulfide minerals, which "would reduce pollutants generated from the tailings basin."[123] However, DNR's EOR and Gale-Tec consulting engineers have opined. "The effectiveness of injecting bentonite through the pond water is subject to concern with regard to reliability of the infiltrations reduction."[124]All FEIS modeling predictions of water quality at the tailings basin were predicated on the assumption that bentonite measures would be implemented and that they would effectively reduce water pollution volumes and concentrations. Regulators can no longer rely on these predictions.

There may be lined dry stack tailings storage facility designs that would comply with Minnesota non-ferrous mining rules, provide dam stability with appropriate factors of safety, and also protect water quality. But PolyMet's proposed wet slurry tailings storage, long-term water ponding, and bentonite amendment proposal on top of the existing LTVSMC tailings basin is unlikely to meet any of these basic requirements. PolyMet's FTB dam permit proposal must be rejected.

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[119] Emails, Spectrum Eng., EOR & DNR, PolyMet Tailings Dam Comments Appendix 6, May 31- June 1, 2017, *supra* Exhibit 15.
[120] *Id*.
[121] D. Sutton, Spectrum Engineering, Memo, (FTB) HydroMet and Stockpiles - review of Barr responses to comments, Feb. 24, 2012, attached as Exhibit 22.
[122] Emails, Spectrum Eng., EOR & DNR, PolyMet Tailings Dam Comments Appendix 6, May 31- June 1, 2017, *supra* Exhibit 15.
[123] PolyMet FEIS, *see e.g*. ES-23, ES-25, 3-4, 3-13.
[124] Gale Tec Eng., EOR, DNR Review of PolyMet's Dam Safety – HydroMet Facility – Permit Application, undated 2017, p. 6, attached as Exhibit 23.

C. Hydrometallurgical Waste Residue Location and Facility

Hazardous waste disposal facilities may not be established or constructed within a wetland or in a location where the topography, geology, hydrology, or soil is unsuitable for the protection of the ground water and the surface water. Minn. R. 7045.0460, Subp. 2. PolyMet maintains that HRF wastes will not meet either federal or state criteria for "hazardous wastes," but this may not be accurate given the way in which Minnesota law defines hazardous waste.[125] Even if the wastes planned for disposal in the HRF were not hazardous, Minnesota law applies the same prohibitions to prevent locating an industrial waste disposal facility on a wetland or area made unsuitable due to topography, geology, hydrology, or soils. Minn. R. 7035.1600, Items D, G.

In Minnesota, only a hazardous waste facility can accept liquids, and these must be removed or solidified at closure. Minn. R. 7045.0532, Subp. 7. Liquids may not be accepted by solid waste facilities and are generally not acceptable for deposit in industrial waste disposal facilities. Minn. R. 7035.3535, Subp. 1, Items F, G; Minn. R. 7035.1700, Item V(1).

It is not clear what Minnesota rules could be interpreted to permit location of the PolyMet hydrometallurgical waste residue facility on top of wetlands and unsuitable soils or what Minnesota rules might allow disposal of 6,170,000 total tons of liquid waste in a facility that is not licensed for hazardous wastes.

It is, however, clear that there are important reasons why disposal of hydrometallurgical waste residues and other PolyMet liquid or semi-liquid wastes on top of wetlands and unsuitable soils should not be permitted. As previously noted, DNR's consulting engineers have explained that the soft ground beneath the proposed residue facility consists of up to 30 feet of slimes, peat and tailings concentrate, which provide an inadequate foundation for the 80 foot high basin.[126] The engineers have underscored, "[T]his system is susceptible to rupture as a result of strains in the geomembrane or synthetic clay liner."[127] "The liner could deform and fail if the existing underlying material cannot support the material added to the basin."[128]

Possible remediation alternatives have been identified, including: 1) PolyMet's preferred pre-load of the soft materials with rock and soil to compress them; 2) installing wick drains to allow water to flow out of the existing material; or 3) removing the existing materials and soft soils before constructing the HRF. DNR's consultants have not dismissed the preload/wick drain concept; they have required that it be re-evaluated due to questions about its performance.[129] However, it is undisputed that existing wetlands and soft soil materials will rebound after the

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125 Minnesota Statutes state: " 'Hazardous waste' means any refuse, sludge, or other waste material or combinations of refuse, sludge or other waste materials in solid, semisolid, liquid, or contained gaseous form which because of its quantity, concentration, or chemical, physical, or infectious characteristics may (a) cause or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness; or (b) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed. Categories of hazardous waste materials include, but are not limited to: explosives, flammables, oxidizers, poisons, irritants, and corrosives." Minn. Stat. §116.06, Subd. 11. The 3,280 pounds of mercury proposed for disposal in the HRF could, without more, mean that HRF waste is "hazardous."

126 EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, p. 5.

127 *Id*., Attachment 2 - Comment Tables, autop. 34.

128 *Id*., p. 6.

129 *Id*.

preload is removed.[130] DNR's consulting engineers caution that even after a preload "it is likely that differential settlement will occur over the length of the liner system, especially after the material becomes normally consolidated again during HRF construction. This variability may cause an excessive amount of strain in the liner system."[131]

PolyMet has consistently characterized use of wick drains as optional.[132] PolyMet has also resisted the alternative of excavating and replacing the HRF foundation materials as "potentially impractical" and has questioned whether excavating the layer of wetlands and soft soils may result in instability of the FTB South Dam.[133]

Since the alternative of excavating wetlands and unsuitable soft soils hasn't been analyzed, WaterLegacy doesn't know which, if any, of PolyMet's concerns are well founded. However, considering the risks of dam failure and toxic leakage if liquid wastes are stored in an unsuitable location managed by an inexperienced operator, WaterLegacy believes that the mitigation alternative for HRF wastes most consistent with Minnesota rule compliance and protection of public health, safety, welfare and the environment would be to require that PolyMet dispose of HRF wastes and wastewater treatment sludge off-site and deny the dam permit for PolyMet's proposed HRF facility.

Contested Case Request

Minnesota law gives the DNR the discretion to order a Chapter 14 contested case proceeding for dam safety permits.[134] Once appropriate design parameters are set and analysis done, whether the DNR proposes to approve or deny FTB and HRF dam safety permits, a contested case proceeding would allow public transparency and the development of a record to address disputed factual issues.

Since many issues pertinent to dam safety permits, such as requirements for perpetual maintenance that determine financial assurance, and the need for removal of water from reactive mine waste, overlap issues that might be raised for a permit to mine, WaterLegacy recommends that contested case proceedings for PolyMet dam safety permits and the PolyMet permit to mine be coordinated and heard by the same trier of fact.

Conclusion

WaterLegacy appreciates DNR's ongoing efforts to engage experts and require additional analysis of PolyMet's proposals and computations.

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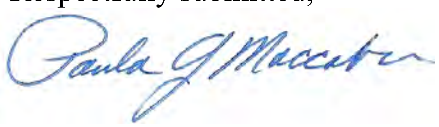
[130] HRF Geotech., p. 34.
[131] EOR Review Team, PolyMet Dam Safety Permit Application Review, *supra*, Attachment 2 - Comment Tables, autop. 34.
[132] HRF Geotech., pp. 6, 14; HRF Mgt. Plan, p. 10
[133] HRF Geotech., p. 41.
[134] *See e.g. In the Matter of Hibbing Taconite Mine and Stockpile Progression and Williams Creek Project Specific Wetland Mitigation*, 2014 Minn. ENV LEXIS 94, OAH Docket No. 11-2004-31655 ORDER DENYING MOTION (BY CLIFFS) TO DISMISS OAH APPEAL (December 15, 2014), pp. 19-20; Beck, Gossman & Nehl-Trueman, *Minnesota Administrative Procedure*, § 4.2 at 47 (2d. ed. 1998 & Supp. 2008); *In the Matter of Rances Barthelemy*, OAH Docket No. 80-1008-31374, AMENDED ORDER ON CROSS MOTIONS FOR SUMMARY DISPOSITION (2014) ("When an agency is not required by law or constitutional principles to initiate a contested case, it is permitted to offer a 'gratuitous hearing'").

However, based on the draft PolyMet FTB and HRF permits, the documents prepared by PolyMet to support its permit applications, and the issues raised by the DNR's engineers and consultants as well as by other experts, we believe that compliance with Minnesota statutes and rules would require the denial of both the FTB and HRF dam permits. Due to failures in PolyMet's investigations, insufficient permit requirements and safety factors, incomplete designs and substantial unresolved questions about design adequacy, the Commissioner cannot at this time determine that PolyMet's proposals are reasonable, that PolyMet has demonstrated the lack of other suitable feasible and practical sites for waste disposal, that the stability of the FTB and HRF dam will be maintained under all pertinent conditions, or that the dams will comply with prudent, current environmental practice throughout its existence.[135]

Fundamentally, approval of draft dam permits for the PolyMet flotation tailings basin and hydrometallurgical residue facility would fail to protect public health, safety, and welfare and the environment.[136]

Respectfully submitted,



Paula Goodman Maccabee
Advocacy Director/Counsel for WaterLegacy

Enclosure: Exhibits 1-23

cc: Minnesota Pollution Control Agency
U.S. Army Corps of Engineers
U.S.D.A. Forest Service
U.S. Environmental Protection Agency
Fond du Lac, Grand Portage and Bois Forte Bands of the Lake Superior Chippewa

[135] *See* Minn. R. 6115.0410, Subp. 8, Items A, D and F.
[136] Minn. Stat. §103G.315, Subd. 3; Minn. R. 6115.0410, Subp. 8. Minn. R. 6115.0300.

Table of WaterLegacy Dam Safety Permit Exhibits

Exhibit 1	DNR Commissioner Landwehr letter to WaterLegacy, (Sept. 29, 2017) (2 pages)
Exhibit 2	D. Dostert & Boyle, DNR Review of PolyMet's Dam Safety- Tailings Basin – Permit Application, Contingency Action Plan, undated. (1 page)
Exhibit 3	Bernedo, Predictive Models & Available Software, USSD Workshop on Dam Break Analysis Applied to Tailings Dams (2011) (38 pages)
Exhibit 4	Mount Polley and Samarco Dam Failure News Articles (2014 & 2015)(14 pages)
Exhibit 5	Figure B-1 in Attachment B to FTB Geotech. Cross-Sections (2017) (1 page)
Exhibit 6	Figure 4.2.3-1 Watershed & Wetlands, PolyMet FEIS (2015)(1 page)
Exhibit 7	Martin et al., Challenges with conducting tailings dam breach assessments, 85th Annual Meeting International Commission on Large Dams (ICOLD) (2017) (11 pages)
Exhibit 8	FERC Engineering Guidelines Risk-Informed Decision Making, Dam Breach Analysis, Excerpt Draft (2014)(16 pages)
Exhibit 9	Wastewater Concentrations Excerpt from PolyMet FEIS (2015) (2 pages)
Exhibit 10	E. Evarts, Area Fisheries Supervisor, DNR Request for Comments - Dam Safety - Construction - St. Louis County - Applications 2016-1383 and 2016-1380 (2017) (1 page)
Exhibit 11	WaterLegacy Letter to U.S. Army Corps re Section 404 Permit Hearing & Review with Exhibits (2017) (134 pages)
Exhibit 12	D. Singh *et al*., Liquefaction Susceptibility of Silty Soils, *Int'l J. of Advances in Sci. Eng. And Tech*., Vol-5, Iss-1 (2017) (4 pages)
Exhibit 13	S.M. Gale and N.M. Lichty, Letter to C. Olivier, Proposal for Geotechnical Engineering Review of Polymet Hydromet. Residue Facility Foundation Design (2017) (2 pages)
Exhibit 14	Dam Safety permit to the Erie Mining Co. for the North East Extension of its taconite tailings basin, permit 81-2000 (1981) (6 pages)
Exhibit 15	Emails, Spectrum Engineering, EOR & DNR, PolyMet Tailings Dam Comments Appendix 6 (2017)(6 pages)
Exhibit 16	B. Johnson, DNR, NorthMet Project Geotech/Hydromet Mgt. Plans (2016) (2 pages)
Exhibit 17	Review and Conference Call Record, EPA review of NorthMet Project Flotation Management Plan (FTMP) (2010) (5 pages)
Exhibit 18	DNR Memo, Dana's recommended direction on PolyMet (2011)(1 page)

Exhibit 19	Geotechnical Stability IAP Summary Memo NorthMet Project EIS (2011) (4 pages)
Exhibit 20	T. Radue. Barr Eng., Email to DNR, PolyMet Follow-Up (2013) (1 page)
Exhibit 21	FERC, Hydropower Safety Guidelines Engineering Guide, Ch. III, Excerpt (2016) (3 pages)
Exhibit 22	D. Sutton, Spectrum Engineering, Memo, (FTB) HydroMet and Stockpiles - review of Barr responses to comments (2012)(1 page)
Exhibit 23	Gale Tec Eng., EOR, DNR Review of PolyMet’s Dam Safety Spreadsheet (2017)(13 pages)

DEPARTMENT OF NATURAL RESOURCES

September 29, 2017

Paula Goodman Maccabee
WaterLegacy
1961 Selby Avenue
Saint Paul, MN 55104

Dear Ms. Maccabee:

Thank you for your letter dated September 27, 2017, regarding the draft dam safety permits for the proposed NorthMet project. Your letter, which you indicate was submitted on behalf of the Center for Biological Diversity, Friends of the Cloquet Valley State Forest, Izaak Walton League-Minnesota Division, and WaterLegacy, included a request for a 30-day or greater extension to the public comment period on the draft permits.

Having carefully considered your request, DNR will not be granting an extension to the public comment period. DNR understands that there is great interest in this project. That is why we chose to provide a 30-day public comment period to allow the public to review and comment on the draft dam safety permits. The 30-day comment period is not required under state law, and we do not typically hold public comment periods on dam safety permits.

Regarding the duration of the comment period, please recall that the two draft dam safety permits released September 15, 2017 are each 7-8 pages in length. The extensive applications and other technical materials on which the draft permits are based have been posted to DNR's project website for many months, beginning with PolyMet's initial dam safety application submittals in July of 2016. As modifications were made to those applications and other documents became available, DNR has updated the project website and provided notification to the Center for Biological Diversity, Friends of the Cloquet Valley State Forest, Izaak Walton League-Minnesota Division, WaterLegacy, and others through the state GovDelivery email system on a quarterly basis. This has been part of DNR's strong commitment to providing the public with timely access to project information that DNR is reviewing. We have done this to ensure transparency, and to facilitate a timely process.

In the instance of the draft dam safety permits, the information posted on our website has included:

- The original dam safety applications and supporting technical documents
- Reference documents
- A dam safety geo-technical report submitted by our consultant, Emmons & Olivier Resources, and additional external dam safety experts
- Revised permit applications and supporting documents to reflect changes to the proposed design
- Monitoring plan, contingency action plan, and test plan
- Draft permits and a dam safety permit fact sheet

I understand that my staff were in communication regarding the Data Practices Act (DPA) request included in your September 27 letter within 1-day of receiving your letter. We have offered to provide immediate electronic access to information gathered in response to a separate DPA request regarding these same draft permits. We have also outlined additional options for responding to your request.

In response to questions raised in your letter, I can also confirm that:

- the "most current DNR approved version" of the "NorthMet Project Geotechnical Data Package" and the "most current DNR approved version" of "NorthMet Project Flotation Tailings Management Plan" referenced in the draft Permit for the PolyMet FTB Dam (2016-1380) are the documents provided in Appendices A and B of PolyMet's May 2017 NorthMet Dam Safety Permit Application for the Flotation Tailings Basin

- the "most current DNR approved version" of the "NorthMet Project Geotechnical Data Package, Volume 2 - Hydrometallurgical Residue Facility" and the "most current DNR approved version" of the "NorthMet Project Hydrometallurgical Residue Facility Management Plan" referenced in the draft Permit for the PolyMet HRF Dam (2016-1383) are the July 11, 2016 Geotechnical Data Package provided on the MDNR PolyMet permitting website and the "Residue Management Plan" provided in Appendix A of PolyMet's May 2017 NorthMet Dam Safety Permit Application for the Hydrometallurgical Residue Facility

You did not supply contact information for the other groups represented on your letter. Therefore, I am providing this response to you and requesting that you share it with the appropriate individuals in the other organizations you have identified as co-signers to your letter.

Thank you for your continued interest in the DNR's review of this proposed project and we look forward to receiving your comments on the draft permits on or before October 16, 2017.

Sincerely,

Tom Landwehr
Commissioner

DNR Review of PolyMet's Dam Safety - Tailings Basin - Permit Application

Section:

Reviewers:

Comment #	Reviewer	Page	Section or Table Number	Comment/Concern	Date Discussed
1	Dana		Buttress memo	How to model buttress. How were base soils modeled? Was peat removed? Plan for maintaining design cross section over time. Minor slump, does it lead to larger issues?	
2	Jason		Instrumentation/Monitoring - 1.0	The plan only discusses cell 2E. Please discuss how water levels would be managed in 1E during the first few years of the project.	
3	Jason		Instrumentation/Monitoring - 2.1.1.2	1st sentence. Please list the multiple types of piezometers currently at the site.	
4	Jason		Instrumentation/Monitoring - 2.1.1.2	Good description of why "b" is placed where it is. Please include description for "a" and "c".	
5	Jason		Instrumentation/Monitoring - 2.2.1	End of 1st paragraph. What is meant by "below existing and PROPOSED LTVSMC coarse tailings"? Is this the dam raises? Please clarify.	
6	Jason		Instrumentation/Monitoring - 2.2.3	Survey once per year of monuments doesn't seem frequent enough during construction. Please provide rationale for frequency.	
7	Jason		Instrumentation/Monitoring - 2.3	What is a dam construction event? Is it the same as a dam raise? Please clarify.	
8	Jason		Instrumentation/Monitoring - 3.2	1st sentence. A normal range of reading could be unsafe. Using the observational method, "expected" or "predicted" seems more appropriate.	
9	Jason		Instrumentation/Monitoring - 3.2	End of 1st paragraph. Please clarify what returning to service means.	
10	Jason		Instrumentation/Monitoring - L Fig. 1	Should include mention of sinkholes or subsidence.	
11	Jason		CAP - 1.2	Error! Resource source not found	
12	Jason		CAP - 1.3	Hazard class listed in the document is Class II, yet the dam breach analysis shows dozens of homes potentially getting wet. Need justification for hazard class recommended and/or need to refine dam breach analysis.	
13	Jason		CAP - 1.5	3rd paragraph. Need further discussion on what is meant by "instrument values to be observed at each instrument location will be established"	
14	Jason		CAP - 2.0	Suggest adding reference to Emergency Action Plan and moving 2nd bullet above 1st bullet.	
15	Jason		CAP - 3.2	We will need to review the plant-wide EAP. Please provide.	
16	Jason		CAP - 4.0	Last sentence. This might affect financial assurance, depending on types of equipment.	
17	Dana		CAP - 5.0	Though I consider the dam breach analysis very good, I have never been completely comfortable with it as it dealt with a water breach. An actual failings that mobilized tailings would be much more serious, The closest house is approximately 1.05 miles to the NE.	
18	Dana		CAP - 5.0	It has been our experience that things happen in the nights and on weekend that don't get noticed until Monday when it is to late to stop or prevent the event from happening.	
19	Jason		CAP - 5.0	Further discussion is needed about warning time, there is only adequate time if the breach is noticed right away.	
20	Dana		CAP - Large Figure 1	Should probably have residences phone numbers also so they could be autodialed in case of an FTB dam failure potential. Contact information should also be ordered by priority. Those at risk are a higher priority than most everybody else.	
21	Jason		CAP - Large Figure 1	Need further information on how the Plant Site EAP and this plan will fit together. Would be better during an emergency to only have to reference one document.	
22	Jason		Bentonite Amendment - 4.1	Please eloborate on why it will take two years to construct the test section. The document doesn't provide much detail on the test section dimensions and scale.	
23	Dana		Bentonite Amendment - General	How big of a "hole" would it take to allow for air exchange and make the remainder of the bentonite barrier ineffective.	
24	Dana		Bentonite Amendment - General	Spighotting bentonite in the tailings during the last couple of years of operations may also be a cost effective option.	
25	Dana		Bentonite Amendment - tree roots.	Tree roots will be an annual problem and have to be quickly removed. How fast can a tree root exceed 30 iches? The slopes and basin would have to be mowed or sprayed annually for centuries.	
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USSD Workshop on Dam Break Analysis Applied to Tailings Dams

Predictive Models & Available Software

Presented by

Carmen Bernedo, PE, MSc

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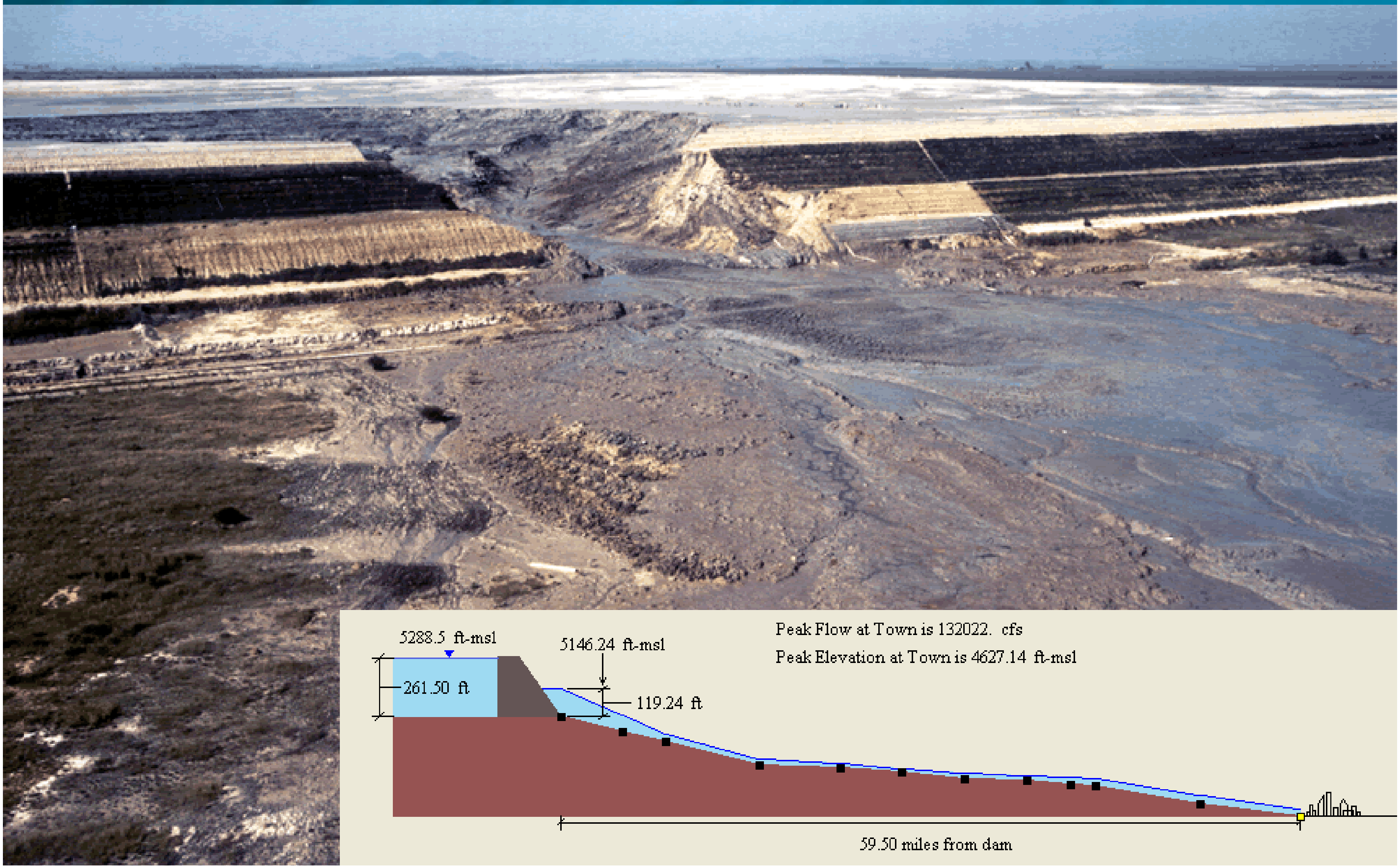
Predictive Models & Available Software



Predictive Models & Available Software

- Antecedents
- Newtonian / non-Newtonian flows
- Available models that allow the simulation of non-Newtonian flows (tailings)
- Other models used in practice

Antecedents

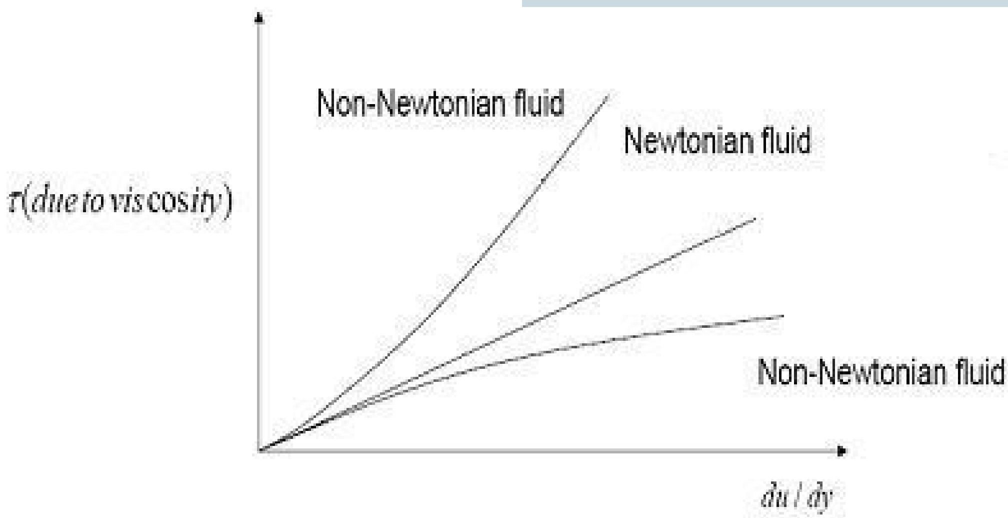
- In the mining industry specific guidelines and/or procedures to perform dam breach analysis for tailing storage facilities (TSFs) and the resulting “flooding conditions” are not available as they do for water dams
- Generally Dam breach analysis and flood-wave routing is needed to assess the effect of a potential dam failure downstream of a TSF, which in turn will guide on the appropriate Emergency Action Plan (EAP) for the TSF under a potential dam breach.

Antecedents

- Most numerical models for dam-break analysis have been developed for water-storage dams. The intention of these models is to predict the flood characteristics depending on dam type and break mechanisms and breach size.
- Significant work is still needed for dam-break analysis of tailings dams. Models need to account for *Hyper-Concentrated Flows* (non-Newtonian).
- Issues:
  - No specific software for modeling dam breaks that contain tailings
  - Modeling dam break parameters predictions
  - Modeling flood propagation and downstream flow predictions
  - Type of failure: Sunny Day /Rainy Day

Newtonian vs. Non-Newtonian Fluids

Newtonian	Non-Newtonian
• Has a constant viscosity with rate of deformation • It is not time dependent • Simple • Water	• The absolute viscosity changes with rate of deformation • Depends on time and thus flow rate • More complicated • Paints, sludges, tailing • There is no simple relationship between the stress and the rate of strain



Fluid Mechanics – Finnemore and Franzini

Newtonian vs. Non-Newtonian Fluids

- Fluids resist flow. This phenomenon is known as viscosity.
- Fluids like water and gasoline behave according to Newton's model, and are called Newtonian fluids. Other fluids such as ketchup, blood, yogurt, mud, and cornstarch paste DON'T follow the model.
- For some fluids (like mud or snow) you can push and get no flow at all until you push hard enough, and the substance begins to flow like a normal liquid. This is what causes mudslides and avalanches.

What Model Should I Use?

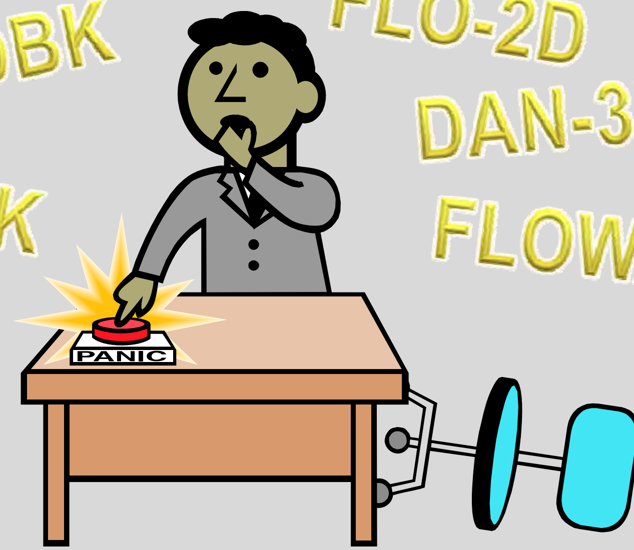
HEC-RAS MIKE

SMPDBK FLO-2D

DAMBRK DAN-3D

FLOWAV

HEC-HMS DAN-W



What will I be modeling?

And what is the main goal?

Predictive Models & Available Software

National Weather Service

SMPDBK

DAMBRK

BOSS

BOSS DAMBRK

FLDWAV

Hungr

DAN-W

J. O'Brien

FLO-2D

Scott McDougall

DAN-3D

Non-Newtonian Models (Water and sediment)

SMPDBK

HEC-RAS

HEC-HMS

MIKE

Newtonian Models (Water)

Some common models

Selecting a Model

- What will the model be used for?
  - Emergency Action Plan
  - Environmental Impact Study
  - Hazard Classification
- How detailed should the results be?
- What information is known?
- Different models may predict different portions of a dam break (hydrograph and routing) more accurately.
- Model Output : APPROXIMATION

  = > CAUTION

Models for Non-Newtonian Flows

- These models allow direct modeling of tailings:
  - DAMBRK
  - FLO-2D
  - FLDWAV
  - DAN-3D

Waihi Tailing Dam, New Zealand

Non-Newtonian Models - DAMBRK

Ajkai Timfoldgyar Tailing Dam, Hungary 2010

- Developed by the National Weather Service in 1984
- Updated by BOSS International
- Predicts the dam breach wave formation and its downstream progression
- Three main features:
  - Ability to describe dam failure mode temporally and geometrically
  - Computation of the outflow hydrograph through the breach
  - Ability to route the outflow through a downstream channel

Non-Newtonian Models - DAMBRK

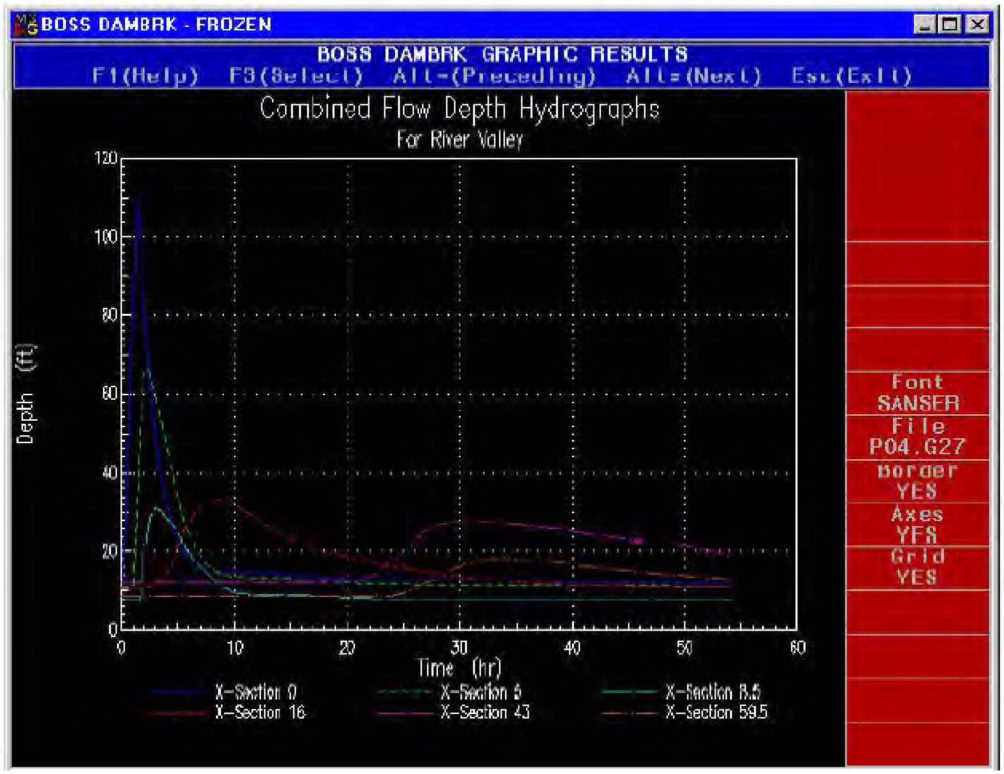
- Good for determining potential influenced area.
- Allows the user to input geometric and temporal data for the dam break to accurately predict the initial breach wave, including modeling piping and overtopping failures.
- Has the ability to route the flow from the breach hydrograph
- The data entry is very flexible and will run the model on limited data, but the more data, the more accurate results obtained.

Non-Newtonian Models - DAMBRK

- Ability to model non-Newtonian flows by allowing the user to assign fluid unit weights, dynamic viscosity, initial shear strength, and stress rate of strain.
- Has the ability to route supercritical, subcritical, or mixed flows for non-Newtonian fluids.
- Case studies have returned sound results for outflow volumes, peak discharges, and peak flood elevations.

Non-Newtonian Models – BOSS DAMBRK

- Developed from original NWS DAMBRK code
- Improvements include:
  - Faster calculations
  - Graphic interface



Non-Newtonian Models – FLO-2D

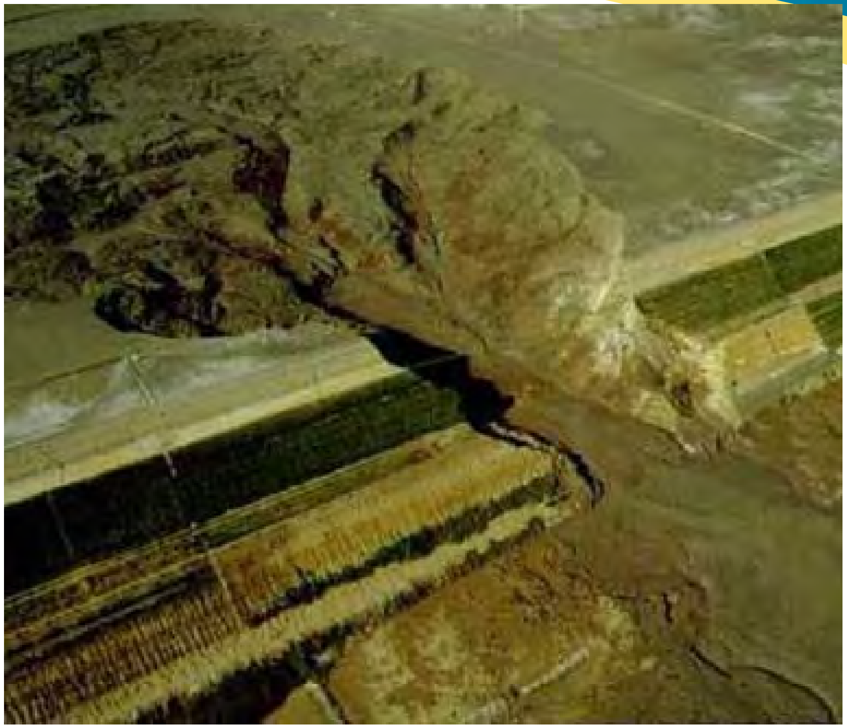
- FLO-2D model grew out of a model developed by Jim O'Brien for FEMA called MUDFLOW in 1989
- Predicts flood hazard, mudflows, and debris flows over alluvial fans.
- Good for predicting flow path and area.
- Uses a grid system to determine the layout of the floodplain based on elevation, roughness factor, and flow reduction factors.
- Both clear and sediment flow can be modeled using a rheological model.

Non-Newtonian Models – FLO-2D

- The discharge is predicted by estimating the depth of flow over each sector and summing up all the sectors on each of the four sides of the grid.
- Allows sediment continuity and has the ability to model remobilization based on changes in the landscape an fluid properties.
- Accuracy is dependent on the density of the grid system and the data available.

Non-Newtonian Models – FLDWAV

- Developed by the NWS to replace DAMBRK.
- Adds wave front tracking for more accuracy and better time based models.
- Allow dam breach prediction and calculating potential concerned area.
- Designed to model rapid flood events from large precipitation events or dam break occurrences.



Merrespruit Dam, South Africa 1994

Non-Newtonian Models – FLDWAV

- Predicts flow through a single stream or network of streams using real time forecasting technology.
- Takes into account terrain and material properties at different time intervals and adjusts flow pattern.
- Based on the 1-D solution to the Saint-Venant equations for unsteady flow.
- Secondary functions allow the model to predict flow through hydrologic structures and river basins.
- Includes special models for dam break analysis, time based flood predictions, pumping situations, and other rapid flow scenarios.

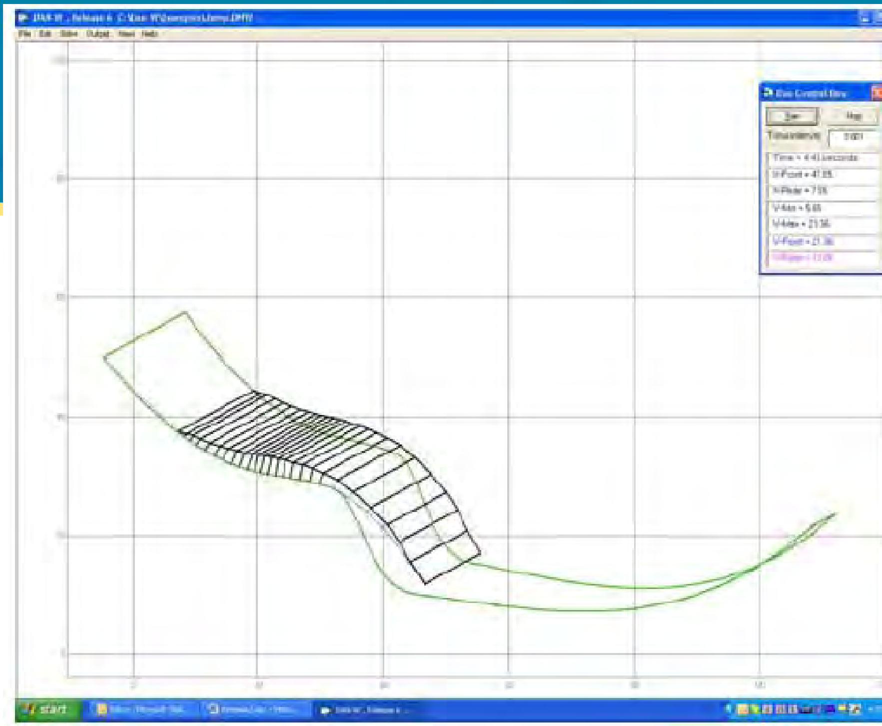
Non-Newtonian Models – FLDWAV

- Allows the flow to change from subcritical to supercritical and back based on location and time interval.
- Can be used to model one dimensional unsteady debris flow (or tailings).
- Caution recommended when use the model to predict flow under bridges, through storm sewers, and through culverts unless it is properly imported as a rating curve.

Los Frailes, Spain 1998

Non-Newtonian Models – DAN-W

- Based on a theory of runout analysis developed by Hungr (1995).
- Based on shallow flow assumptions and is best suited to shallow mass movements, where the flow thickness is at least an order of magnitude less than the length of the moving mass and the movement vectors are approximately parallel with the bed.



- A profile of the travel path (including entrainment zones) and the source area, and the width of the path is needed.
- The solution may be unstable in certain cases where the flow is deep, or where abrupt changes of slope occur.

Non-Newtonian Models – DAN-3D

- Developed by Scott McDougall as a PhD thesis in 2006.
- Runs on the same basic principles as DAN-W but adds the ability to model flow over 3D surfaces.
- Designed to model landslides at high velocity from non-Newtonian fluids and solids.
- Purpose is to predict the impacted area from the slide.

Ajkai Timfoldgyar Tailing Dam, Hungary 2010

Non-Newtonian Models – DAN-3D

- Four Key Features
  - Simulate flow over complex 3D terrain
  - Prediction of internal stresses and strains
  - Ability to account for entrainment of material in the flow path
  - Predict alterations in flow path and properties depending on terrain
- A digital terrain model (topography) of the area is needed.

Non-Newtonian Models – DAN3D

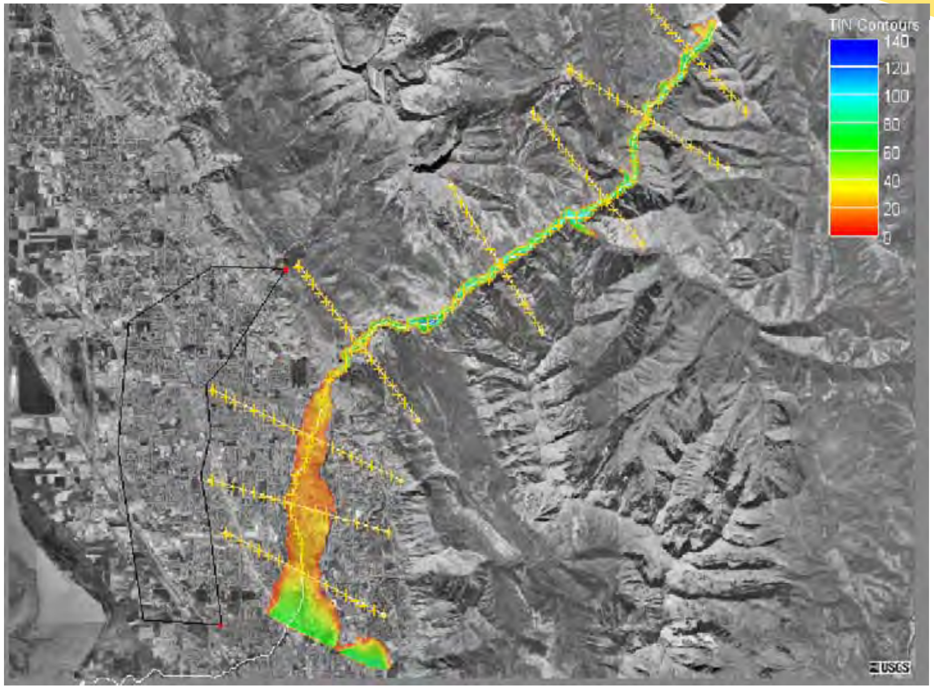
- Based on the two-dimensional Lagrangian solution of unsteady flow over three dimensions.
- Uses flow velocity and depth calculated from the model to predict the impacted area.
- It does not model abrupt changes in terrain or flow type because it smoothes out the results.

Other Models (Newtonian Flows)

- CCHE2D-DAMBREAK
  - two-dimensional shallow water equations
  - The University of Mississippi, 2005
- SMPDBK
  - NWS
- HEC-RAS
  - USACE
- MIKE

Other Models – SMPDBK

- Developed by the NWS as a simpler version of DAMBRK
- Good at obtaining dam classification and potential dam break risk
- Returns virtually the same results as the normal DAMBRK software in simpler cases

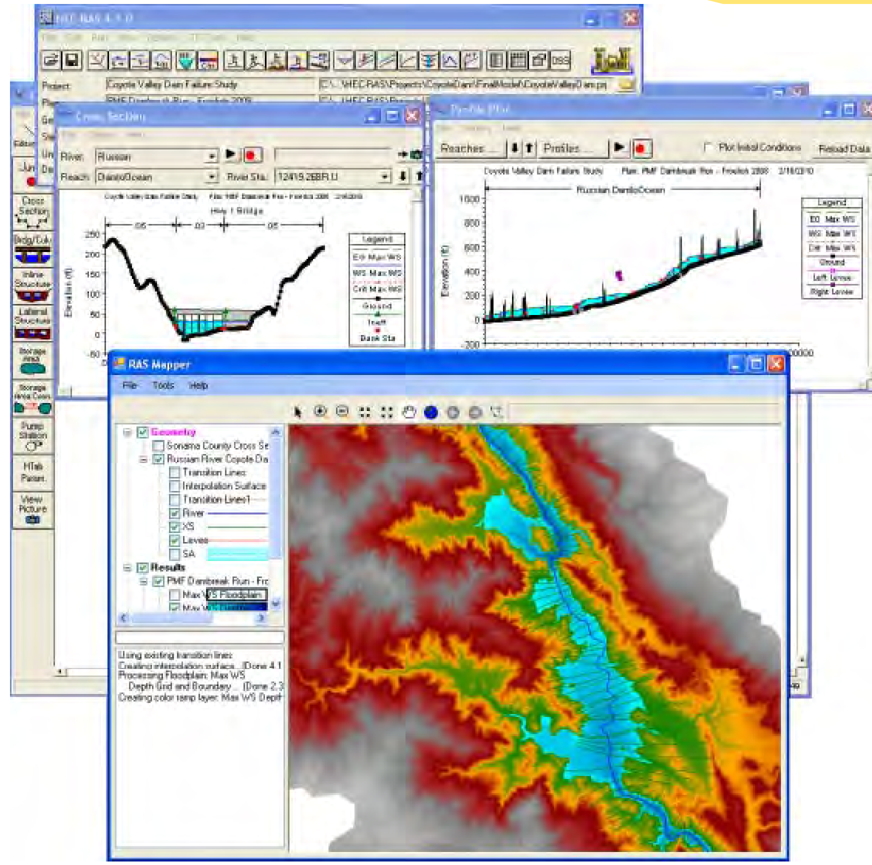


Other Models – SMPDBK

- Quick and easy to use and does not require as many inputs as DAMBRK
- Three assumptions to simplify the model:
  - Rectangular and constant initial breach
  - Constant reservoir surface
  - Peak flow time equal to the breach development time
- Limitations can be helped by providing an equivalent breach width value and dam break time.

Other Models – HEC-RAS

- HEC-RAS was developed by the U.S. Army Corps of Engineers
- A routing method for modeling how water moves downstream
- Does not model non-Newtonian fluids
- Good at predicting downstream flooding effects from an upstream event, such as a dam break



Other Models – HEC-RAS

- Simulate the resulting flood wave front and downstream consequences of an upstream event.
- Models downstream effects by reading the results of dam break analysis.
- Three options to get initial dam break flood wave:
  - Compare dam failure to past failures of similar magnitude
  - Predict hydrograph equations from past dam failures
  - Use the model

Other Models – MIKE 21

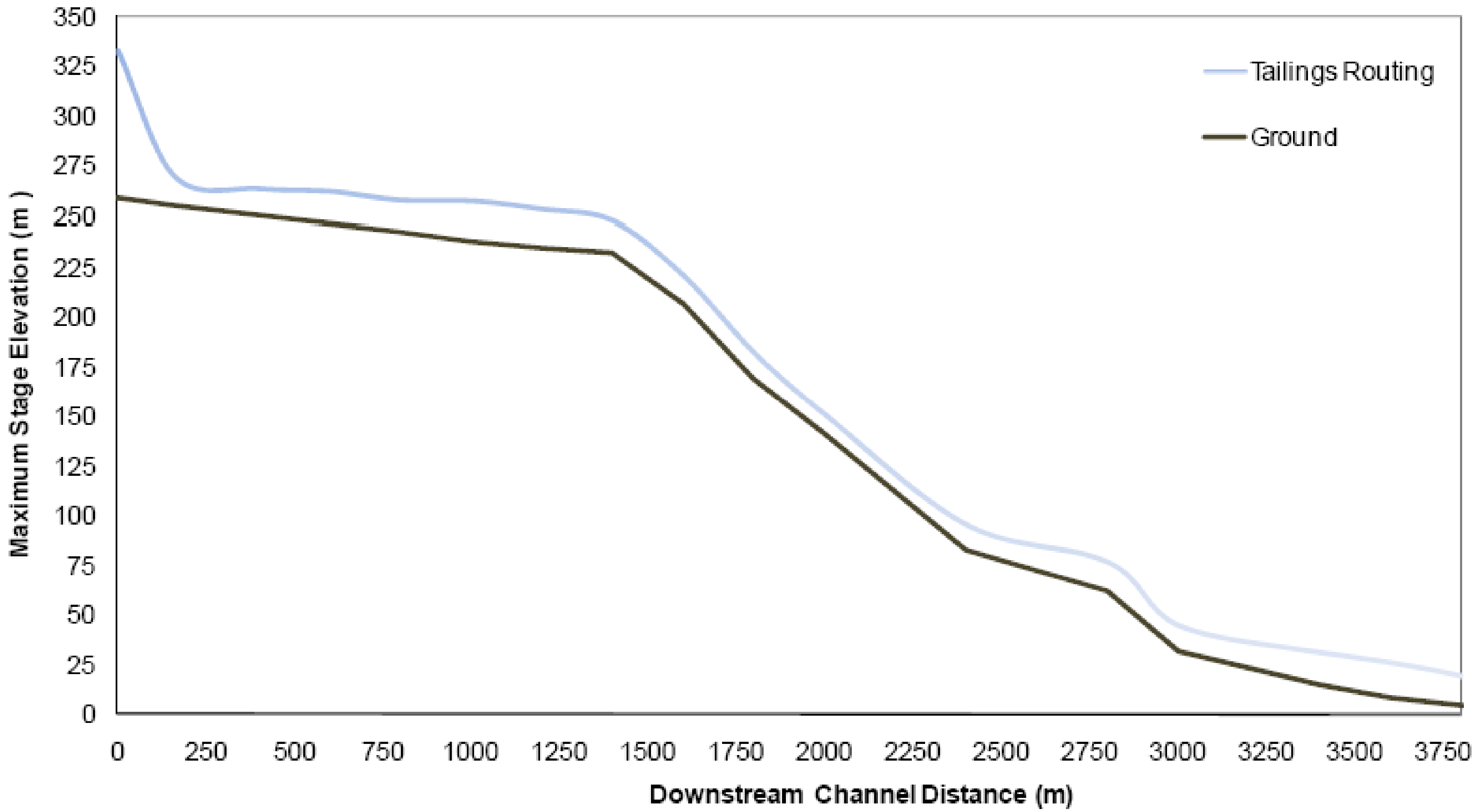
- Two-dimensional software based on the original MIKE 11 model
- Focuses on flow of Newtonian fluids over initially dry terrain
- Good for analysis to estimate potential effected areas

Los Frailes, Spain

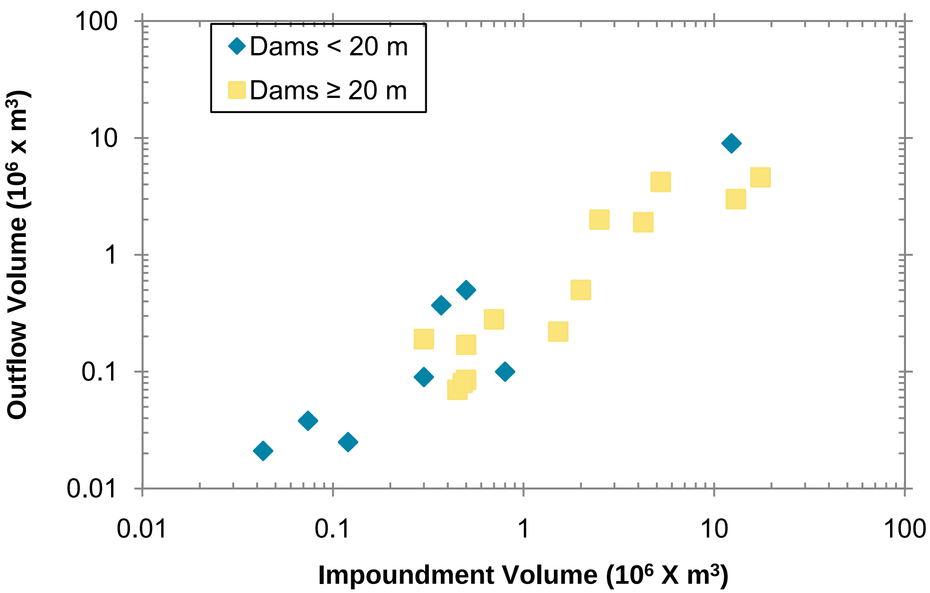
Other Models – MIKE 21

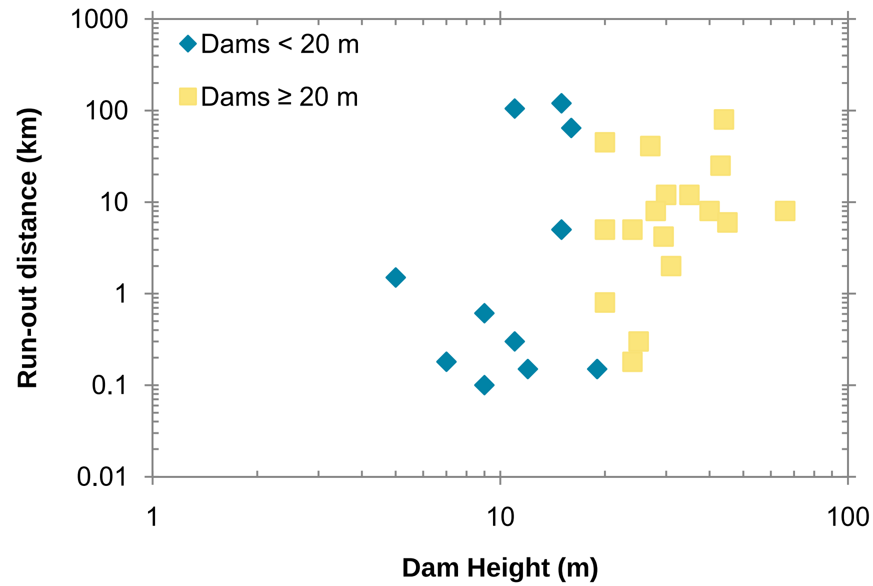
- Predict a wide range of floodplain situations in two dimensions
- Allows sub-critical, super-critical and mixed flows to be modeled
- Based on solutions to depth average equations that describe the conservation of mass an momentum.
- Caution should be used when modeling steeply rising floods and shallow wave fronts

Case Study - Downstream Routing

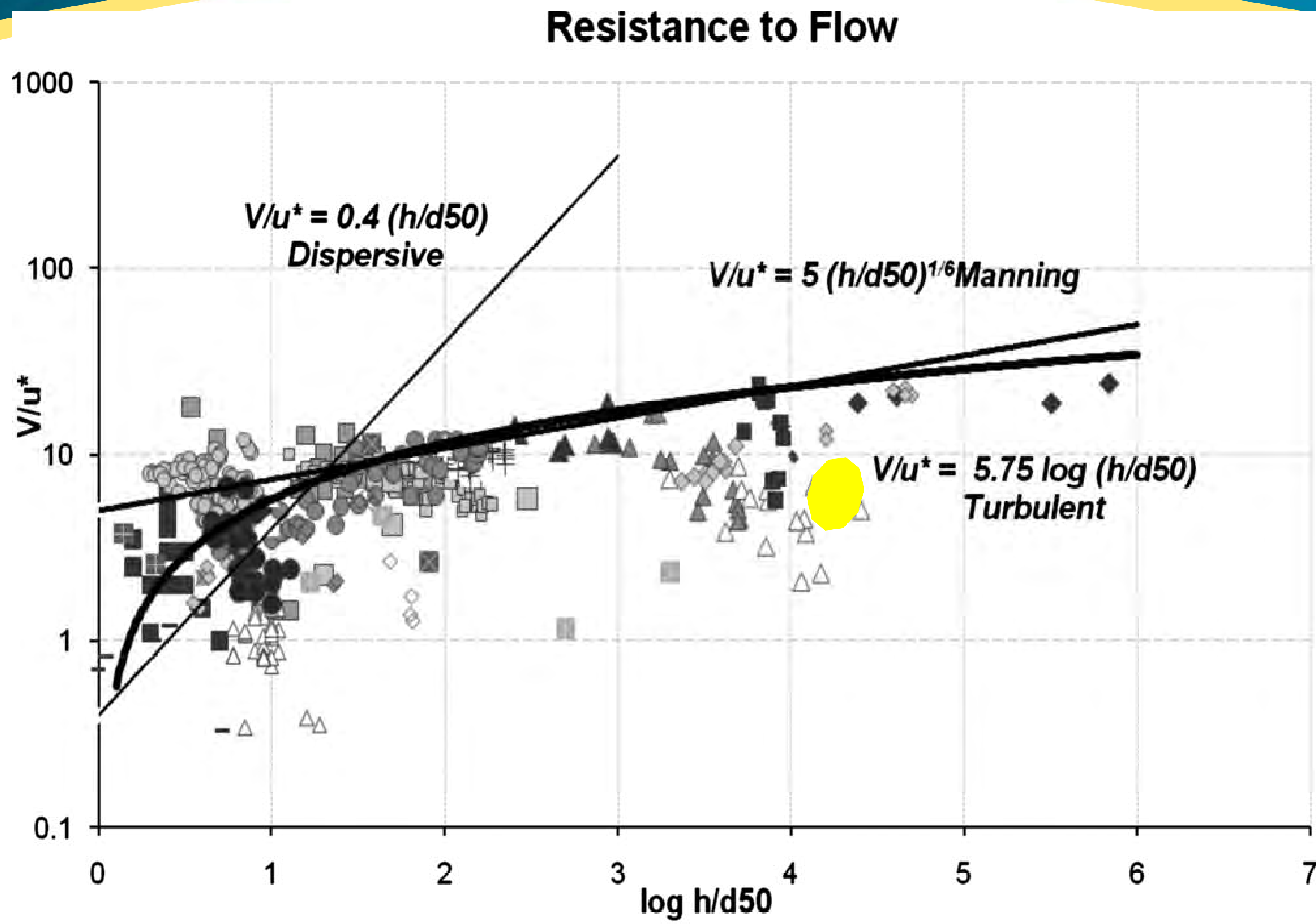


Comparison with Historic Dam Failures (Rico et al., 2007)





Resistance to Flow for Sediment Hyperconcentrations (Julien et al., 2010)



Conclusions

- It is a complex process. Even for water dams only a few decades of research has been done
  - Water (Dam breach process, dam breach parameters significant uncertainty)
  - Tailings (Non Newtonian, Two Phase Flow, properties may change with time, dam breach process and routing)
- The objective of the model could be:
  - Hazard Classification
  - EAP
  - Influence Area for Environmental Studies

Conclusions

- With different models available it is important to define the goal of the analysis
  - Newtonian vs Non-Newtonian
- Model outputs provide approximations. There is always uncertainty
- Water, sediment and chemistry are key components of the dam breach tailings flow characteristics
- The routing from a tailings dam breach moving downhill is determined by the volume of flow, the characteristics of the breach in the dam and the slope of the hillside
- Chemical properties not included in Non-Newtonian models which add uncertainty to the results obtained

Recommendations

1. Several models are using in practice. But at present we are lacking of a robust flow model.
2. Available empirical correlations such as those of Rico et al. (2007) for tailing dam breaks can be applied to provide a first estimate on the volume of tailings spills, tailings run-out distance. Furthermore, the worst case scenario estimation based on the envelope curves developed from historic dam failures from tailings dams can be very useful.
3. It is key to look at historic dam failures to “calibrate” our assumptions and results.

Thank You!
☺

Mount Polley mine tailings spill nearly 70 per cent bigger than first estimated

GORDON HOEKSTRA, VANCOUVER SUN 09.03.2014 |

Waste material and water from the Mount Polley mine tailings pond spills from Hazeltine Creek into Quesnel Lake on Aug. 5. *JONATHAN HAYWARD / THE CANADIAN PRESS*

Imperial Metals' estimate of the size of the spill from its Mount Polley mine tailings dam collapse is nearly 70 per cent greater than the initial estimate.

The B.C. government has estimated that 10 million cubic metres of water and 4.5 million cubic meters of finely ground rock containing potentially-toxic metals was released by the collapse of the dam on Aug. 4. (http://www.vancouversun.com/health/Imperial+Metals+given+deadline+dealing+with+di

But Imperial Metals has estimated the size of the spill at 10.6 million cubic metres of water, 7.3 million cubic metres of tailings and 6.5 million cubic metres of "interstitial" water. That's enough water and material to fill nearly 9,800 Olympic-sized swimming pools.

Interstitial water is the water suspended in the spaces between the finely ground rock of the tailings.

"It's a bit disconcerting — its speaks to the crudeness of the initial estimate," said Mining Watch Canada program director Ramsey Hart of the increased spill estimate.

Imperial Metals did not respond to a request Wednesday for comment.

Hart said there will need to be a better accounting of the spill's size, including the volume of tailings deposited in the lake and in the Hazeltine Creek watershed.

The early numbers were best estimates, later refined by Imperial Metals, said B.C. Mines Ministry spokesman Ryan Shotton in a written statement.

"The company is undertaking work to fully characterize the chemistry of the tailings and water that have been released. This work will include testing for a full suite of parameters, including metals," the statement said.

University of B.C. mining engineering professor Scott Dunbar said he didn't believe there would be a significant difference in the composition of the interstitial water and the water above the tailings in the storage facility. The company has said the water above the tailings was near drinking-water quality.

And Dunbar said while the tailings certainly have been physically damaging, the science suggests they will not be chemically damaging.

That's because the tailings are not acid generating, noted Dunbar, the head of UBC's Norman B. Keevil Institute of Mining Engineering.

Acid-generating rock is a problem for the environment because the sulphides in rock release the metals in minerals trapped in the rock, he explained.

"But they have to go through every square metre, or square five metres (of the spilled tailings), and check to see if this in fact is the case," added Dunbar. "And if that is the case, and it's not damaging, then the cleanup could be reshaping the landscape, reseeding. In the extreme, it's removal. And that will be expensive."

Hart said he would also like to see more reporting on the geochemistry of the tailings materials and on the potential for metal to leach from them.

Several test results of the sediments within the tailings storage facility and outside of it have shown low but potentially significant arsenic and selenium concentration, the province has said.

Hart also said, however, he believed the chemistry of the interstitial water could be different from that of the water above the tailings.

"The water has been in contact for different amounts of time — and the fact that there are low sulphides doesn't necessarily mean there won't be metal leaching because things like selenium, arsenic and zinc all come out of mine wastes without the acid rock draining that Imperial Metal keeps saying won't happen," said Hart.

The rush of water and tailings scoured Hazeltine Creek and poured the water and some of the tailings into Quesnel Lake. Coho salmon and rainbow trout spawn in Hazeltine Creek. Some of the water and tailings also entered Polley Lake, a small lake adjacent to the mine site.

While provincial water tests continue to show the water in Quesnel Lake meets drinking guidelines, the province has warned residents not to drink cloudy water. Residents have reported a plume of sediments in the lake that shows up and disappears. Tests have shown some elevated levels of metals that exceed drinking and aquatic life guidelines in water containing sediments.

Residents, First Nations and environmental groups also say they are concerned about the long-term effects of the spill, including on salmon.

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Mount Polley Mine's Imperial Metals hosted a meeting this week in Likely to update residents on remediation work since the Aug. 4 tailings breach

Mine still supplying drinking water to Quesnel Lake residents

Five months after the Mount Polley Mine tailings impoundment breach last August, Quesnel Lake residents continue to drink bottled water.

MONICA LAMB-YORSKI / Thu Jan 15th, 2015 8:00am / NEWS

Five months after the Mount Polley Mine tailings impoundment breach last August, Quesnel Lake residents continue to drink bottled water supplied by the mine.

"We're not used to living out of jugs and water bottles," said Skeed Brokowski who along with his wife operates Northern Lights Fishing Lodge on Quesnel Lake.

Before the breach they routinely sent water samples to Interior Health for their business.

"We always got our drinking water from the lake and never had a problem," Brokowski said.

During a recent visit to Vancouver, he noticed he was actually opening his mouth while having a shower.

"We're tight-lipped when we're in the shower here because you just don't know," he said.

Looking out onto the lake from his home Thursday morning, Brokowski said he thought the lake did look a little better, but that it will take generations for it to return to normal.

"We used to be able to see 37 feet and four inches down into the lake, now we can see about two feet," he said. "When MLA Donna Barnett says everything is still beautiful out here, it is but the difference is when you look at the lake and Quesnel River, now it's pea-soup green."

He said he wants the mine to restart.

Aside from running the fishing lodge for 46 years, the Brokowskis have made a living mining and logging.

"We're not angry with the mine employees. Mount Polley has done everything they can possibly do, but this thing is big and that stuff is going to be in there forever. We're really angry at government."

Originally Mount Polley Mine had paid for water filters, but filters couldn't filter out the suspended particles.

"The average human hair is 15 microns and the suspended particles are five microns," said Mount Polley Mine vice-president of corporate affairs Steve Robertson. "We tried a number of filters but just couldn't find an effective filtering system that would get those really fine particles out that was practical."

Some of the filters that did work eventually plugged up in two days, he added.

"We've known this for a while so that's why we've continued with our delivery of clean drinking water and will continue with that system."

The company is also continuing to put the pre-filters on people's homes for household water use.

Brokowski said three weeks before the breach they put their lodge on the market.

Three interested parties — two from Europe and one from Texas — contacted them.

“After the breach they couldn’t run away fast enough,” Brokowski said.

“That’s life, but it happens to be our life. Our property assessment has gone up considerably too and we cannot even afford to pay the taxes.”

According BC Assessment, the total assessed value for the 355 waterfront properties located on Quesnel Lake is $67,706,601.

ABC NEWS

Brazil dam burst: 17 dead, dozens missing as mudslides flatten a village and engulf homes at BHP co-owned site

Updated Fri 6 Nov 2015, 9:43pm

Firefighters have rescued about 500 survivors from a torrent of mining waste that killed at least 17 people and destroyed a village after two dams burst in southeastern Brazil.

PHOTO: A rescue helicopter searches the village of Bento Rodrigues covered in red toxic mud from the burst mine dam. (AFP: Christophe Simon)

RELATED STORY: BHP-owned mine dam bursts in Brazil killing 17, devastating town

MAP: Brazil

They searched frantically for survivors after the mudslide erupted from waste reservoirs at the partly Australian-owned iron ore mine.

The torrent ripped the roofs off some houses and left villagers clinging to their roofs.

"There was a horrible noise and we saw the mud approaching. We ran for it. It is a miracle that we are still alive," said Valeria de Souza, 20, with a baby in her arms and tears in her eyes.

The mudslide flattened Bento Rodrigues, a village of about 600 people near the southeastern city of Mariana in the historic mining region of Minas Gerais.

PHOTO: Rescuers are searching for more survivors in Bento Rodrigues. (AFP: Douglas Magno)

Ms De Souza spoke to the media after arriving at a gymnasium in Mariana, where 150 survivors from the destroyed village were being housed.

There were 17 people officially confirmed killed and 50 injured, "but more bodies have been found," said Adao Severino Junior, the fire chief in Mariana.

He warned that more than 40 people could be missing.

"There is no way to survive under that material," he said of the mudslide.

Fifteen-year-old Marcos Junior de Souza told the Folha de Sao Paulo newspaper he fled across the rooftops to escape the torrent.

"All my life I had heard people saying the dam was going to break," he was quoted as saying.

"I never thought much of it until the water flooded my house."

Environmental damage 'enormous'

Firefighters said they had rescued 500 people who were covered in iron and mineral deposits that were then washed off.

PHOTO: A rescue helicopter searches the village of Bento Rodrigues covered in red toxic mud from the burst mine dam. (AFP: Christophe Simon)

The local Mariana miners' union said the sludge was toxic, but the company operating the mine, Samarco, said it was "inert" and contained no harmful chemicals.

Officials and experts said the mud threatened nearby wildlife.

"The environmental damage is enormous," said one of the state prosecutors investigating the disaster, Carlos Ferreira Pinto.

Most of the village's inhabitants work for Samarco, jointly owned by BHP Billiton of Australia and Vale of Brazil.

Samarco said the causes of the rupture were not known.

Experts at Sao Paulo University's Seismology Centre said four small earthquakes were recorded in the region on Thursday, though it was unlikely such small tremors would break a dam.

AUDIO: BHP to investigate as at least 15 people killed by torrent when mining dam burst in Brazil (PM)

Shares in Vale and BHP Billiton plunged on Friday on the Sao Paulo and London stock exchanges.

AFP

Topics: mining-industry, mining-environmental-issues, disasters-and-accidents, accidents, brazil

First posted Fri 6 Nov 2015, 6:10pm

BHP says Brazil plans $5bn legal suit over Samarco disaster

30TH NOVEMBER 2015

SAVE THIS ARTICLE EMAIL THIS ARTICLE

BY: ESMARIE SWANEPOEL
CREAMER MEDIA SENIOR DEPUTY EDITOR: AUSTRALASIA

FONT SIZE: - +

PERTH (miningweekly.com) – Mining giant BHP Billiton said on Monday that it had not yet received any formal notice of legal action from Brazil, after the country's federal and certain state governments announced on Friday that a $5.2-billion legal claim would be instituted against the company, its joint venture (JV) partner, Vale, and the JV vehicle Samarco.

The legal action was reportedly to fund clean-up costs and damages following the November 5 tailings spill at the Samarco operation.

To date, 13 fatalities have been reported with a further six people remaining missing.

Operations at the Samarco project continue to remain suspended and clean-up work has started in the Barra Longa area, focusing on access roads, housing and bridge repairs.

BHP reported on Monday that both Samarco and local oxygen uptake as a result of the spill, metal concentrate levels in the water system have remained unchanged, and that the tailings were composed of materials that were nonhazardous to human health.

The JV partners have previously said that they would set aside $260-million as an emergency fund to assist the community members affected by the spill.

A preliminary agreement with Brazilian prosecutors in Minas Gerais would guarantee that the funding would be used for a range of emergency measures related to prevention, mitigation, remediation, and compensation for environmental and social effects of the incident.

The JV partners on Friday also announced plans to establish a voluntary, non-profit fund to support the recovery of the Rio Doce river system.

The fund would initially be sponsored by Vale and BHP, but additional funding would be sought from other private, public and non-government organisations. The initial value of the fund was still being defined.

The fund would finance the rescue and recuperation effort of the river system, including the recomposition of riparian forest, water quality and aquatic fauna, as well as helping to rescue the biodiversity of the river basin.

EDITED BY: MARIAAN WEBB
CREAMER MEDIA SENIOR RESEARCHER AND DEPUTY EDITOR ONLINE

Cities

Threat

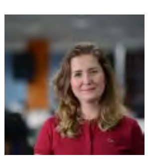
Analysis shows the presence of mercury, arsenic, iron and lead in the Rio Doce water

"To give you an idea, the amount of arsenic found in the sample was 2.6394 milligrams, and the acceptable one is at most 0.01 milligrams," said Mayor Neto Barros.

Posted 12/11/2015 at 17:53

Updated 11/11/2015 at 10:37 p.m.

Fonte: Gazeta Online



Paula Stange Rosi

prosi@redegazeta.com.br

Prefect of Baixo Guandu shows result of laboratory analysis of water

The laboratory analysis of the samples of Rio Doce water, collected in Minas Gerais, indicates the presence of heavy metals in a concentration above the acceptable level. The information was confirmed by the mayor of the city of Baixo Guandu, Neto Barros, in the early afternoon of this Thursday (12).

According to the mayor, the presence of metals such as mercury, aluminum, iron, lead, boron, barium, copper, among others was detected. "To give you an idea, the amount of arsenic found in the sample was 2.6394 milligrams, and the acceptable one is at most 0.01 milligrams," Barros quoted.

The mayor also said that there is 100 km of toxic material down the river. "We found practically the entire periodic table inside the water. I want to see what Vale's president will do to help all the people," he shot.

This week, the Baixo Guandu Autonomous Water and Sewage Service (Saae) sent an expedition to Minas Gerais to collect samples of the water that is descending with the second flood. The dense mud mass was found by technicians in Governador Valadares, about 200km from the border with Espírito Santo.

Since the breakdown of Samarco dams in the mining town of Mariana last Thursday, experts have warned of the impact of the tailings coming to the Rio Doce.

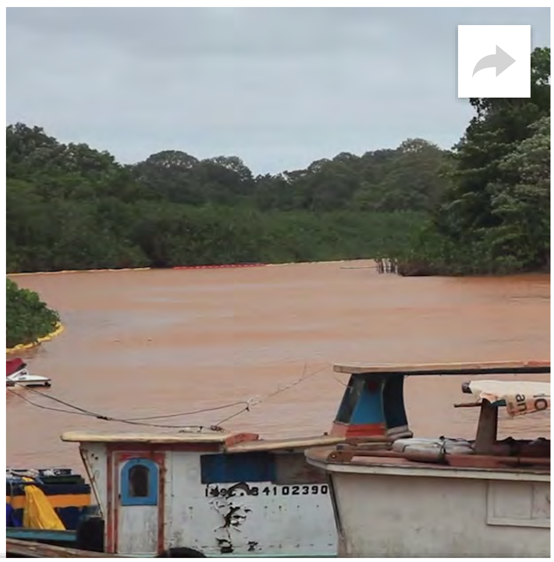
According to Eduardo Duarte Marques, a researcher at the Geological Survey of Brazil, in Belo Horizonte (MG), dam reject is predominantly composed of inert substances, but iron ore may eventually contain portions of metals such as arsenic, antimony, zinc and copper . "At certain ore extraction points there may be higher concentrations of these metals - which would make the sludge really harmful. However, to know the concentration, you will need to do chemical analysis," he said.

The mayor of Baixo Guandu says that the result of water analysis is extremely worrying. He also ordered the blockade of the Vitória-Minas railroad to be carried out today to prevent the transportation of ore passing through the municipality. At the end of the afternoon, the city council, according to Neto Barros, will put machines on the rails to prevent the passage of the train carrying the ore. "We need urgent responses to the problem that affects the entire region," he said. "We will not allow any mining activity, and if there was no mobilization in the city, the consequences could be even worse."

The other side

By way of note, mining company Samarco said it is unaware of the technical report that indicates the presence of heavy metals in the mud. "The company reinforces that the waste is classified as inert and non-hazardous material, according to the Brazilian standard of code NBR 10004-04, which means that it does not present risks to public health and the environment. , the reject is composed basically of water, iron oxide particles and silica (quartz).

Watch videos of dam rupture



00:11 / 02:10

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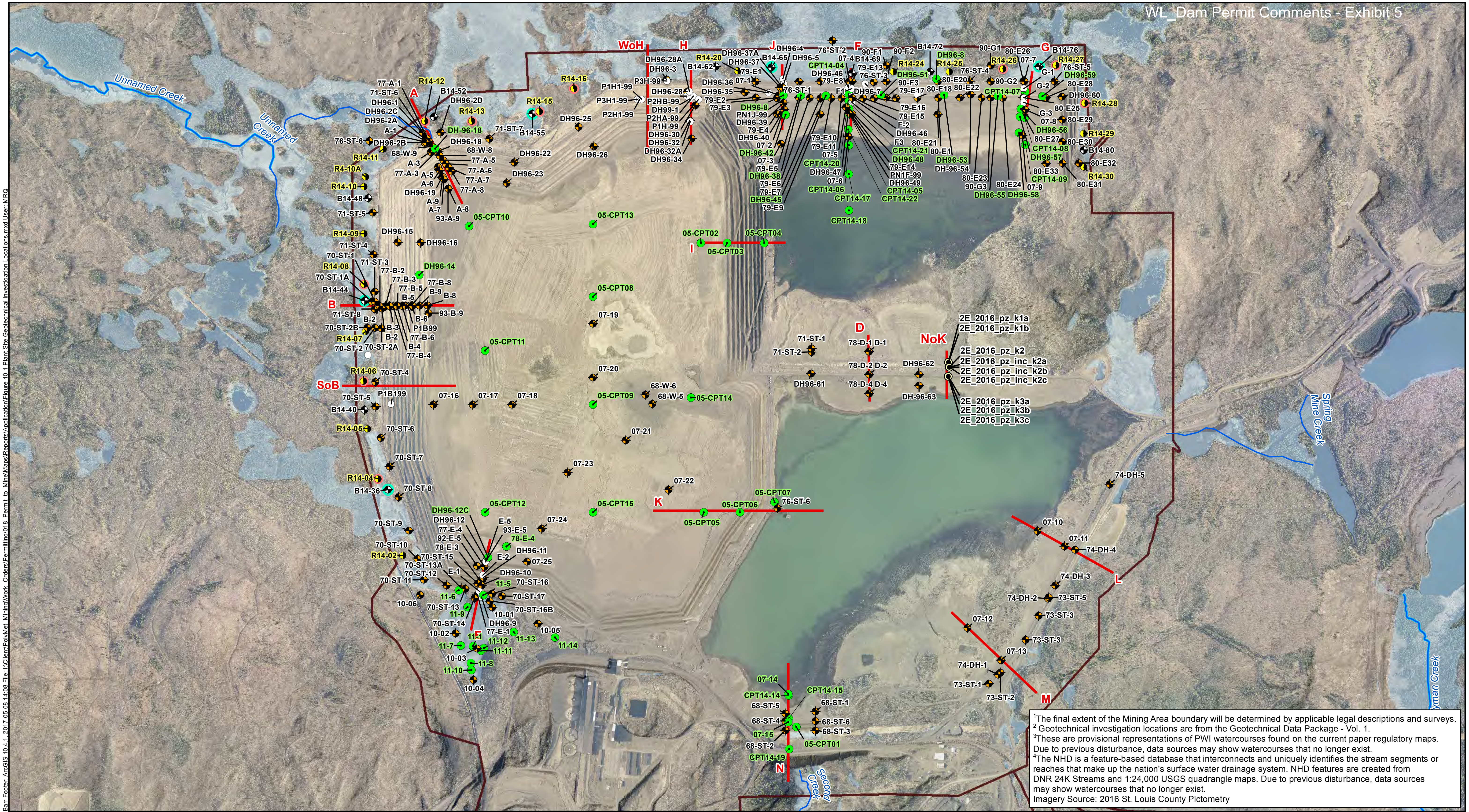
samarco Valley

SEE COMMENTS



[1]The final extent of the Mining Area boundary will be determined by applicable legal descriptions and surveys.
[2] Geotechnical investigation locations are from the Geotechnical Data Package - Vol. 1.
[3]These are provisional representations of PWI watercourses found on the current paper regulatory maps. Due to previous disturbance, data sources may show watercourses that no longer exist.
[4]The NHD is a feature-based database that interconnects and uniquely identifies the stream segments or reaches that make up the nation's surface water drainage system. NHD features are created from DNR 24K Streams and 1:24,000 USGS quadrangle maps. Due to previous disturbance, data sources may show watercourses that no longer exist.
Imagery Source: 2016 St. Louis County Pictometry

Mining Area[1]
Cross Section Alignment
Geotechnical Investigation Locations[2]
2016 Locations
2014 Rotasonic Location
2014 Rotasonic Location with a Piezometer
2014 Boring Locations
2014 Boring Locations with Packer
Historic Test Locations[2]
Other/Unknown
CPT Location
SPT Location
Public Waters Inventory (PWI) Watercourses[3]
National Hydrography Dataset (NHD) Rivers & Streams[4]
Wetlands

0 1,500 3,000
Feet

BARR

PLANT SITE GEOTECHNICAL INVESTIGATION LOCATIONS
NorthMet Project
Poly Met Mining, Inc.

Figure B-1
Permit to Mine Application

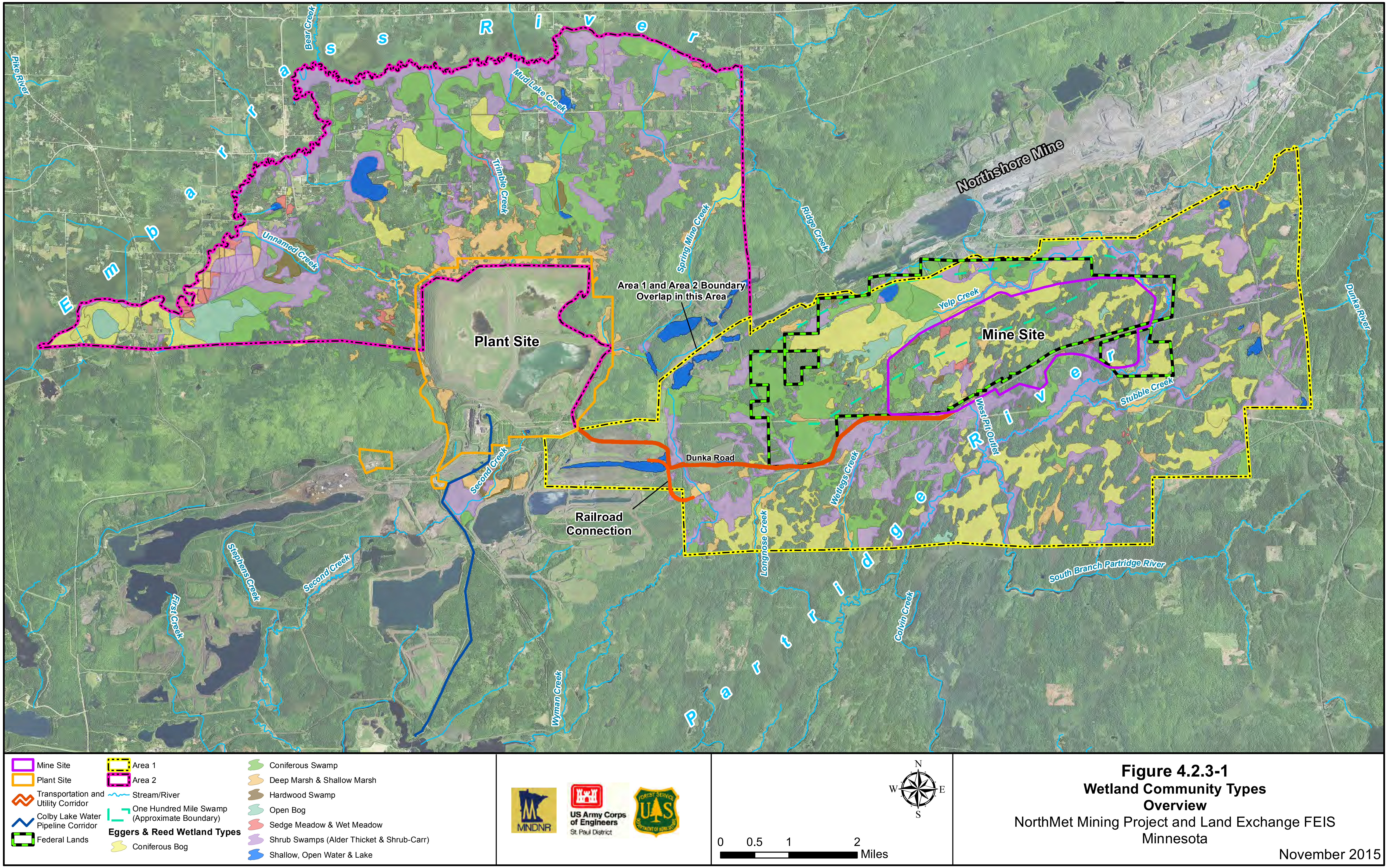


Figure 4.2.3-1
Wetland Community Types
Overview
NorthMet Mining Project and Land Exchange FEIS
Minnesota
November 2015

July 3–7, 2017
Prague, Czech Republic
85th Annual Meeting
of International Commission on Large Dams

Challenges with conducting tailings dam breach assessments

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ABSTRACT

Following the recent tailings dam breaches at Mount Polley, Canada, and Samarco, Brazil, the mining industry and regulatory agencies worldwide increased the demand for tailings dam breach analyses and flood inundation mapping. The results of such studies are used to determine the hazard classification of a dam through the assessment of dam failure consequences, to support emergency preparedness and response planning, and to inform environmental assessments. Dam breach studies involve the selection of a dam failure mode and appropriate hydrologic conditions, the approximation of the breach size, the estimation of the volumes of released tailings and water, and the modelling and mapping of the runout pattern of released materials. There is considerable uncertainty in each step of the analysis, which combined with the lack of a standardized approach for completing such studies, necessitates that practitioners rely on experience and sound professional judgement to conduct the studies and assess the results. In this paper, we review some of our recent experiences with tailings dam breach assessments and discuss challenges encountered and lessons learned for various case studies, including selecting credible failure modes, selecting appropriate hydrologic parameters, determining the range of possible breach parameters, and estimating the volumes of released tailings.

1. INTRODUCTION

Tailings dam breach assessments are commonly expected and required for operating and planned Tailings Storage Facilities (TSFs). These studies are primarily used to determine the hazard classification for a dam, for the preparation of emergency preparedness and response plans, and sometimes for environmental impact assessments and alternatives assessments for newly proposed or expanding facilities. Various dam breach guidelines are available to help direct such studies, but they were originally developed for water retaining dams and are not specific to, nor fully applicable for tailings dams (e.g. FEMA 2013, CDA 2007a, CDA 2007b, ICOLD 1998). The Technical Bulletin *Application of Dam Safety Guidelines to Mining Dams* issued by the Canadian Dam Association (CDA 2014) would appear to address this situation, but rather than prescribing procedures for conducting tailings dam breach analyses, it is limited to identifying "some specific issues that should be considered during the design and safety evaluation of mining dams." The CDA subsequently formed a working group for developing guidelines specific to tailings dam breach assessments, and the first draft is expected in the fall of 2017. In the interim, practitioners must largely rely on their own initiative, judgment and experience to frame a TSF dam breach assessment, although useful information is available in a few recent conference proceedings, such as those by Martin et al. (2015) and Strauss et al. (2016).

The key differences between a water retaining dam failure and a tailings dam failure are the volume of outflow and the solids contained in that volume. A breach of a water dam typically results in the discharge of the entire impounded volume of water above the breach, and the outflow has a relatively low solids content, which originates from the embankment material and the mobilization of settled sediments from the reservoir. A breach of a tailings dam, in contrast, often results in the discharge of the entire supernatant pond volume, but does not consistently result in the full discharge of the impounded tailings volume. The outflow, however, typically has a high solids content due to the mobilization of stored tailings solids.

A dam breach of a TSF that stores a sizeable supernatant pond typically results in two discharge mechanisms: (1) initial flood wave, and (2) tailings slumping and/or flow of liquefied tailings. These mechanisms occur in sequence following a catastrophic failure of a TSF dam for all cases where there is a supernatant pond present, and are distinctly different in terms of the potential risk they pose to the downstream environment. The initial flood wave is caused by the discharge of the supernatant pond, which erodes and mobilizes the stored tailings solids and embankment construction materials. The flood wave typically propagates far downstream causing extensive erosion and large inundation. Following the initial flood wave, additional mobilization/slumping of tailings material occurs due to the loss of confinement and local steepening of slopes created by the initial discharge. The flow of slumped tailings has a much lower water content than the initial flood wave, and though it can have extensive deposition in areas immediately downstream of the facility, it typically results in a considerably smaller inundation footprint farther downstream. For cases where the entire tailings mass has a potential to undergo liquefaction, discharge of even larger tailings volumes could be expected, which could result in a substantially larger tailings inundation footprint.

This paper discusses specific challenges encountered while conducting tailings dam breach assessments for several case studies. These challenges included insufficient topographic information, uncertainty in the selection of adequate hydrologic conditions, selection of credible failure modes or appropriate breach parameters, and the selection of downstream boundaries of hydrodynamic models. Some of the case studies presented are in the public domain, while others are discussed in more general terms due to confidentiality agreements with our clients.

2. BREACH PARAMETERS

The quantitative assessment of potential consequences caused by the initial flood wave from a breach of a tailings facility requires estimates of the volumes of water and tailings released during the breach. The total volume of the breach outflow is a key piece of information used to estimate the peak discharge, the physical characteristics of the breach (width and side slopes) and the time of failure (an estimate of how quickly the breach would develop). These characteristics are used to develop a dam breach hydrograph, which is subsequently routed through the downstream drainage network to estimate the inundation limits of the flood.

The volume of the breach outflow includes the volume of tailings that would mobilize due to the discharge of supernatant pond from the breached TSF. The volume of mobilized tailings can be estimated assuming full mixing of water with tailings solids, as discussed in Fontaine and Martin (2015). This approach is based on the potential of the available free water in the TSF to entrain and mix with tailings solids, while considering the physical characteristics of the deposited material (total mass of deposited solids, density of the tailings mass, degree of saturation, and average dry density). If the volume of stored tailings is small relative to the volume of water in the facility, this approach tends to result in estimates of all tailings solids being mobilized, and in turn, if the volume of stored tailings is large relative to the volume of water, it results in estimates of small volumes of tailings solids being mobilized. An alternative and commonly applied approach is to use an empirical relationship developed by Rico et al. (2007), which predicts that approximately 37% of the impounded volume comprised of tailings solids, supernatant water and interstitial water, constitutes the breach outflow volume. This approach may at times result in unrealistic estimates, particularly in cases where the volume of water in the TSF is small relative to the volume of stored tailings, or when liquifaction is a known risk. It should be noted that the above two approaches do not explicitely consider the tailings mass rheology (viscosity and yield stress), which would play a significant role in the case when liquefied tailings behave like a Bingham plastic fluid (Jeyapalan et al. 1983; Seddon 2010; Kulesza 2011).

The other breach parameters are similarly challenging to define. There are no industry standards for tailings dams, and the typically referenced equations are in most cases empirical and largely based on past failures of water retaining dams less than 30 m high, and as such they are not particularly applicable to large tailings dams. The selected parameters, however, have a considerable impact on the final results. Several equations should therefore be considered to determine a possible range of values for various breach parameters, especially considering that various breaching software packages, in our experience, often produce values closer to the low end of the range that may not be sufficiently conservative for dam safety purposes. A number of commonly used equations that are used to determine the range of peak flows, breach widths, side slopes and times of failure have been summarized by Wahl (1998): Johnson and Illes (1976), Singh and Snorrason (1982, 1984), MacDonald and Langridge-Monopolis (1984), Costa (1985), Bureau of Reclamation (1988), Von Thun and Gillette (1990), FERC (1993), and Froehlich (1995a, 1995b). Other common approaches are found in Rico et al. (2007), Froehlich (2008), and Pierce et al. (2010). Most of these empirical equations are based on dam height and estimated outflow volume. Further discussion on methods for predicting the breach parameters, the range of values obtained, and the physical constraints that should be considered is provided in Martin et al. (2015).

3. CASE STUDIES

Our recent experience with various tailings dam breach assessments indicates that a high level of professional judgement and experience is required in order to make reasonable assumptions and overcome the uncertainties that are encountered in every step of the process. Three case studies are presented and specific challenges are discussed, including the selection of appropriate hydrologic parameters, selection of credible failure modes, determination of study extents, estimation of volumes of released tailings, and determination of the possible range of breach parameters. All these considerations have substantial impacts on the results and study outcomes.

3.1 Afton TSF Dam Breach Assessment

3.1.1 Project Description

The Afton TSF is located 12 km west of the City of Kamloops, BC, Canada. The facility was designed in accordance with the Extreme dam hazard classification to withstand the Maximum Credible Earthquake (MCE) and pass the Probable Maximum Flood (PMF). It was constructed in 1976-1977 and has been under care and maintenance since mining operations ceased in 1997. Production at the Afton Mine began in 1977 and the embankments were progressively raised throughout the operating period. Additional information about the project can be found in Akkerman and Martin (2015) and Adams et al. (2017).

The Afton TSF incorporates two two-zoned earthfill/rockfill dams with engineered filter zones, riprap lined spillway, two seepage collection ponds, and upstream diversion structures sized for a 1 in 200 year peak flow event (Figure 1). The Afton Mine ceased operations before reaching the full mine life and the dams were never raised to their ultimate design height; however, the dams were constructed to their ultimate design width. Consequently, the East and West Dams were overbuilt for conditions when operations ceased, and the crests of the dams were left at approximately 100 m wide. A portion of the East Dam was buttressed by a waste rock dump that is higher than the East Dam itself, while the West Dam was constructed with relatively shallow downstream slopes (shallower than 2H:1V). The spillway is designed to pass the PMF and has an invert constructed 2 m below the crest of the East Dam. The spillway consists of a 50 m wide riprap lined channel (Figure 2) that transitions to an unlined earth channel, which curves along the toe of the East Dam and leads to a haul road located along the perimeter of the Historic Afton Open Pit. The sand tailings beaches have been capped and revegetated, and the TSF pond is mostly dry (Figures 1 and 3).

Figure 1. General arrangement of the Afton TSF

Figure 2. Riprap lined spillway entrance with reclaimed tailings beach in the foreground and waste rock dump on the right side of the frame; looking downstream (northeast)

The climate in the project area is typical of the dry BC Interior Region, with generally low total precipitation and high evaporation, and correspondingly low streamflow rates. Located in the rain shadow of the Coast Mountains, this area has a semi-arid steppe climate characterized by generally cool, dry winters and hot, dry summers, with low humidity. Temperature and precipitation records for the mine area indicate mean annual temperature and precipitation values of 7.3°C and 305 mm, respectively, while the annual potential evapotranspiration (PET) was estimated using the Thornthwaite equation at approximately 565 mm.

Figure 3. TSF pond on July 9, 2013; looking northeast

3.1.2 Challenges with Defining Credible Failure Modes

A tailings dam breach study was completed in 2014 according to the Canadian Dam Association (CDA) "Dam Safety Guidelines" (CDA 2007a), which specify that "To assess the potential consequences [of a dam breach], the potential failure modes for the dam and the initial condition downstream from the dam should be determined…". Defining credible modes of failure for the Afton TSF proved to be rather challenging; it was hard to envision the possibility of any substantial dam failure given the dryness of the local climate, the large capacity of the spillway, the robustness of the embankment design, and the current embankment condition. The challenges were specifically related to selecting the breach locations and the initial pond water levels for plausible failure scenarios.

Breaching through the deepest dam section represents a common conservative modelling approach, as it results in the largest outflow volume and the highest peak discharge. The highest dam section is the West Dam at its north end, which is 75 m high; however, because a large area along this end of the West Dam has a reclaimed tailings beach developed to the crest of the dam, a pond cannot form adjacent to the dam. Accordingly, a potential failure through this deepest section would likely result in a deformation of the dam crest and possible slumping of tailings, but would not result in the largest possible flood wave and associated downstream inundation that could potentially result from the discharge of free water.

The West Dam at the south end is 30 m high through the deepest section, and has a tailings beach developed to approximately 6 m below the dam crest. A pond may develop adjacent to the dam in this area, and consequently, a catastrophic failure in this location is credible and could result in the discharge of stored water. However, the outflow volume and the peak outflow discharge would be considerably less for a 30 m high dam compared to a 75 m high dam. On the opposite side of the Afton TSF, the south end of the East Dam is buttressed by a waste rock dump that is higher than the dam itself, and the north end has a reclaimed tailings beach developed to the crest of the dam, so these are not realistically probable breach locations. The only credible location for a potential breach of the East Dam is through the unlined portion of the earth spillway, however, consideration of this is contrary to the common practice of disregarding the spillway as a potential breach location.

Setting the initial pond volume proved to be equally challenging to selecting the breach location. The actual annual variation of the water level in this facility is not known since water levels have not been continuously monitored during the care and maintenance period. However, it is anticipated that the water level in the TSF remains several metres below the spillway invert at all times for the following reasons: (a) this is a non-operating facility and there is no requirement for water storage; (b) the natural inflow from the majority of the upstream catchment is diverted around the facility; and (c) the historic climatic conditions indicate that the annual evaporation is higher than the annual precipitation, leaving the facility in a natural deficit condition.

The maximum normal operating water level is typically used for a sunny day dam breach assessment. The Afton TSF is in care and maintenance, and hence, such a condition does not apply. Based on LiDAR surveys, the maximum water storage volume available from the tailings surface to the spillway invert is estimated at 3.3 Mm^3 (million cubic meters); however, the observed pond volume is much smaller and on the order of 0.2 Mm^3. Given this small volume of water and the relatively large embankments with shallow slopes and 100 m wide crests, sufficient erosion and material mobilization to scour the embankments all the way down to the existing ground elevation is not likely to occur in a realistic sunny day dam breach scenario. Rather, it is more reasonable to expect that the amount of released tailings volume would be reduced compared to a breach eroding through the full height of the embankment, resulting in substantially less downstream inundation. In fact, with only a small pond volume present in the Afton TSF, it is likely that a sunny day failure would only result in an embankment deformation followed by localized slumping of tailings, with essentially no downstream inundation.

In a flood induced dam breach scenario, and if prior to the onset of a PMF the initial water level was set at the maximum observed level, the peak water level in the facility during the PMF event would be 0.8 m below the dam crest, assuming a functioning spillway. In the case where the initial water level is assumed to be at the invert of the spillway, the facility would still retain 0.4 m of freeboard during the PMF. Overtopping of either the East or West Dams would require that the 50 m wide, 2 m deep spillway is fully or partially blocked, which is unlikely for the current conditions of this facility considering the large size of the spillway, the sparse ground cover in the drainage basin, and the active nature of the neighbouring mine site that results in opportunities to observe and correct any potential blockage. As such, it is difficult to conclude that arbitrarily increasing the volume of water stored in the facility and/or blocking the spillway to force overtopping during a flood event represents a credible failure scenario.

3.1.3 Results of the Conducted Dam Breach Assessment

Despite the above discussion on credible failure modes and considering the current state of practice of dam breach and inundation studies for mining dams, the authors of the Afton TSF dam breach study found themselves having to proceed with conservative but unrealistic assumptions, which required ignoring the realities of very dry climate conditions and current low pond water levels. In the sunny day failure scenarios, the pond water level was assumed to be at the spillway invert, since the true variation of the pond level was unknown and this represented the most conservative assumption. The observed small pond and the dry climate, however, make the occurrence of a large flood wave in a sunny day breach quite improbable. In the flood induced failure scenarios, the starting pond water level was also assumed at the spillway invert, and the West and East Dams were assumed to breach when the pond was at its maximum level during the PMF flood.

Setting the initial water level at the spillway invert for both the sunny day and flood induced scenarios resulted in modelling a release of an excessive volume of water (approximately 3 Mm^3 above current volume). This additional volume of water resulted in larger outflow volumes, greater peak discharges, and higher downstream inundation levels than would have been predicted with a smaller and more realistic pond volume. The modelled failure of the West Dam for sunny day and flood induced scenarios resulted in large inundation areas from the dam to Kamloops Lake, located 12 km downstream, and flooding of a mobile home park and numerous farmlands and associated human dwellings.

In summary, a flood induced scenario would not cause overtopping, but would likely result in discharge through the large spillway in the East Dam with flows directed into the Historic Afton Open Pit located a short distance downstream, while the areas downstream of the West Dam would not be impacted. For a sunny day scenario, foundation or embankment slope failures are not probable due to buttressing and shallow dam slopes. Internal erosion and piping are unlikely considering the dry facility, while a catastrophic earthquake would not results in significant dam crest deformation thus discharge of tailings is also unlikely, but if it occurred the impacts downstream would be limited due to the lack of water in the facility.

3.2 Dam Breach Assessment for a Proposed Project

3.2.1 Project Description

A dam breach assessment was undertaken for a proposed project in Northern Canada to aid in determining the hazard classification of the dam and support the environmental impact assessment of the project. The proposed project is a hard rock mine with a high throughput and a mine life of over 20 years. The proposed TSF is a large facility designed to store tailings, waste rock, and potentially acid generating (PAG) material, which requires subaqueous deposition. The normal operating pond volume is estimated to be substantial at approximately 20 Mm^3.

The TSF is located in a remote area, in the headwaters of a small creek in a V-shaped valley between the mountains. The outflow from the breached dam would flow down a small creek, which drains into another watercourse, followed by meandering and braided rivers ever increasing in size. There are no lakes or reservoirs along these rivers, the first larger populated area is approximately 300 km away, and the ocean is over 2,200 km away.

3.2.2 Challenges with Flood Wave Routing

One of the challenges with this dam breach assessment was determining the downstream boundary of the one-dimensional model for flood wave routing. The initial downstream boundary set at 80 km from the dam proved to be insufficient, as the incremental water depth at this location was still between 2 and 3 m high, depending on the modelled scenario. This finding led to the need to extend the model for another 110 km to the confluence with another large river.

For much of the modelled river system, only coarse topographic data was available which made river channel definition challenging. 1 m and 5 m LiDAR contours were available for the first 20 km downstream of the dam, but only 30 m contours were available from NTS (National Topographic System) mapping for the remaining area. Combining the two types of data resulted in two issues. The first was that the contours did not align well. The second was that the crude 30 m contours did not define the topography of the large braided river valleys well and the GIS software was not able to interpolate between the river contours correctly (Figure 4a, b). Good river valley definition was needed for “cutting” the cross-sections for the flood routing model that were set 250 m apart. Conducting field surveys to validate such a large number of cross-sections along the 190 km modelling reach was not practical for this level of assessment. These issues required considerable time for computer manipulation in order to adequately define the cross-sections of river channels and adjacent floodplains along the wide U-shaped river valleys.

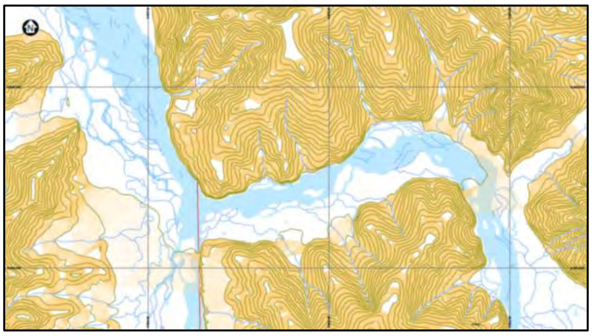

Figure 4. Confluence of two rivers: (a) Google Earth image; (b) 30 m contours for the same area

3.2.3 Results of the Dam Breach Assessment

For the sunny day scenario, the modelled front of the flood wave arrived to the first downstream confluence 11 km downstream of the dam in 0.7 hours following the breach, with an incremental increase in flow depth of 10 m. The flood wave arrived to the end of the model 190 km downstream, approximately 32 hours after the breach occurred, with an incremental flow depth of less than 1 m. The peak of the breach flood wave was estimated to be approximately equal to the mean annual flood at this location. Given that river channels can typically contain the mean annual flood within their banks, the sunny day breach flood wave was assumed to be contained within the natural river channel at this location.

For the flood induced scenario, it was assumed that the PMF event centered over the mine site was coincident with a 200 year flood in the larger rivers in the downstream drainage network. The modelled front of the flood wave arrived downstream at the first confluence point in 0.8 hours following the breach, with an incremental increase in flow depth of 13 m. The flood wave arrived at the end of the model approximately 18 hours after the breach, with an incremental flow depth above the 200 year flood level of about 1 m.

The results of the study indicate that a flood wave caused by a major dam breach of this TSF storing a large amount of tailings and water would be considerable and would propagate tens or hundreds of kilometres downstream, likely causing extensive erosion and floodplain deposition along the way. Considering the 30 m contour spacing and the assumed shape of river channels and their adjacent floodplains in the model, there is considerable uncertainty associated with the accuracy of the inundation mapping and the estimates of flow depths. The inundation results need to be viewed critically when trying to assess impacts to fisheries and wildlife, and may not be adequate for highly detailed quantification of such impacts. Any assessment of environmental impacts based on these results should be completed at a comparable level of effort and detail. However, the results of this study are considered useful as they prompted further discussion related to the design and size of the TSF, the placement of waste rock within the facility, the separation and placement of PAG tailings, as well as the amount of water stored in the facility.

3.3 Dam Breach Assessment for an Operating Mine

3.3.1 Project Description

A preliminary dam breach model and inundation assessment were conducted for an existing mine in the USA that is located upstream of a densely populated area. The TSF is a facility with large volumes of stored tailings and water, and with embankments that were raised over several decades. The tailings beach in the TSF is up to 2 km long and the supernatant pond is positioned far away from the embankments except in one corner of the facility. The open pit is located downstream of the TSF, and it is anticipated that in case of a dam breach the outflow would primarily discharge into the open pit. In order to assess the flood wave pathways, map the inundation limits, and determine whether the flood wave would potentially bypass the open pit and travel beyond the mine property, a two-dimensional hydrodynamic model was developed for the mine site. A risk assessment conducted for the facility indicated that a sunny day piping scenario represents a credible failure mode and the most likely dam breach scenario for the current condition of the TSF. This scenario was the only scenario modelled during the preliminary dam breach assessment.

3.3.2 Challenges with Defining Dam Breach Parameters

As discussed in Section 2, breach parameters are challenging to define, with peak flows being particularly important considering the impacts they have on the final results. In this study, the outflow volume in the initial flood wave was determined using the approach outlined by Fontaine and Martin (2015), and a range of mixed tailings solids of 25-65% by weight was used to determine a range of potential outflow volumes. This range represents sediment laden flows with solids contents observed in water floods, mud floods, and hyperconcentrated flows (e.g. Pierson and Costa 1984, O'Brien 1986, Gusman 2011). Figure 5 illustrates the calculated range of outflow volumes for saturated beach conditions, a range of observed historic pond volumes from 18.5 Mm^3 - 37.0 Mm^3, and a range of 25-65% mixed solids by weight.

The maximum observed supernatant pond volume of 37 Mm^3 was used to determine the breach parameters in combination with 50% mixing of solids with free water, which resulted in a total outflow volume of 76.8 Mm^3. The range of values for peak discharge, average breach width, breach side slopes, and time to fail was then determined using various empirical equations, as discussed in Section 2. The results are shown in Table 1, with the lowest value shown in green and the highest value shown in red.

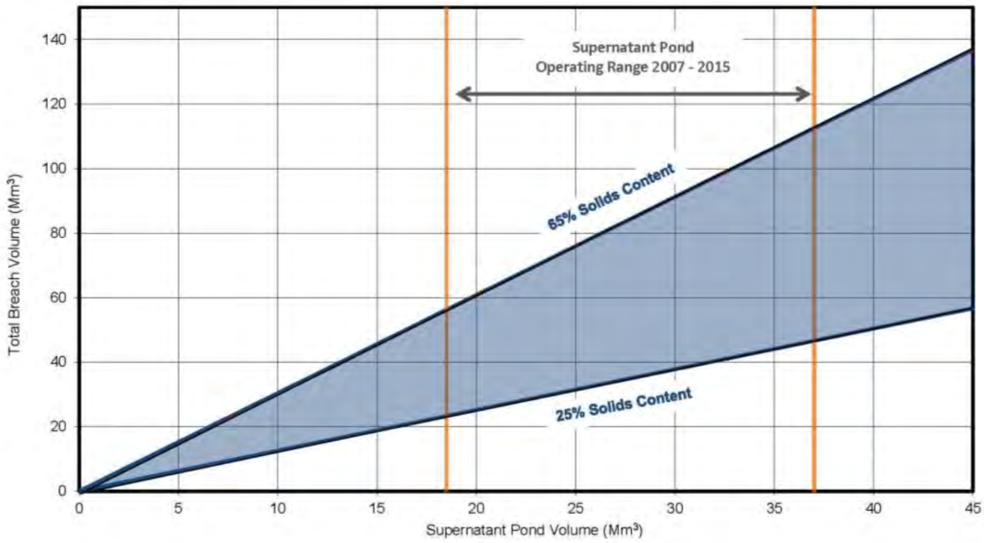

Figure 5. Relationship between supernatant pond volume and total breach outflow volume

Table 1. Breach parameters based on empirical relationships by various authors

Methodology	Peak Flow m³/s	Time to Fail hours	Average Width m	Side Slope Ratio H:1V
Johnson and Illes, 1976	-	-	4 - 251	-
Singh and Snorrason, 1982, 1984	-	0.25 - 1.0	168 - 419	-
Macdonald, 1984	12,296 - 40,110	2.59	73	0.50
Costa, 1985	9,735	-	-	-
Bureau of Reclamation, 1988	60,021	2.56	233	-
Von Thon and Gillette, 1990	-	1.17	249	0.33 - 1.0
FERC Guidelines, 1993	-	0.1 - 1.0	84 - 419	0.25 - 1.0
Froehlich, 1995	28,413	0.71	140	0.9 - 1.4
Rico et. al., 2007	12,523	-	-	-
Froehlich, 2008	-	0.59	108	0.7 – 1.0
Pierce et al., 2010	14,781 - 24,321	-	-	-
Mean	**26,076**	**1.26**	**184**	**0.76**

The main challenge during this assessment was the selection of the peak flow, as the model outcomes are very sensitive to this parameter. Without guidelines or strong research to suggest which empirical equation or breach modelling software better predicts dam breach peak flows, this significant decision is left up to the practitioner. Considering the large range of peak flows and other breach parameters (Table 1), three peak flows covering this range were selected to conduct flood routing modelling: 14,000 m^3/s, 28,000 m^3/s, and 48,000 m^3/s. The breach width and time to fail were selected such that the outflow hydrographs would result in the selected peak flow value, while the breach side slopes were kept the same at 0.7 for all three scenarios. The selected failure mode was modelled as piping. The ultimate breach bottom width and time to fail ranged from 67 m and 2.5 hours for the low peak flow of 14,000 m^3/s, to 187 m and 0.8 hours for the high peak flow of 48,000 m^3/s.

3.3.3 Results of the Dam Breach Assessment

The flood routing results indicate that most or all (in case of the low peak flow scenario) of the breach outflows end up in the open pit, 3.3 km downstream of the breach location. The start of the flood wave reaches the open pit in 15 minutes for the high peak flow scenario, and a much longer 40 minutes for the low peak flow scenario due to its much flatter hydrograph. None of the outflow volume reaches the mine property, 5.5 km downstream, for the low peak flow scenario, and only 0.1% and 2.8% of the total outflow volume does for the medium and high scenarios, respectively. The mine property boundary is reached in approximately 25 minutes and 60 minutes for the medium and high scenarios, with respective maximum flow depths and velocities of 0.5 m and 0.75 m/s and 2.5 m and 2.25 m/s.

The results of this assessment indicate that the downstream inundation extent is very sensitive to the method selected for determining the peak flow, which in turn depends on the estimate of the volume of mobilized tailings solids and total outflow volume. Considering the uncertainty in selecting any of these values, this assessment demonstrates the importance of evaluating a range of equally possible scenarios. The downstream populated area would not experience any breach effects in the low peak discharge scenario and only minor impacts in the medium peak discharge scenario, but possible loss of life conditions in the high peak discharge scenario. The results of this study prompted discussions related to the volume of stored water in the TSF and emphasised the importance of storing as little water as practicable to limit possible outflow volumes in the case of a breach. Furthermore, the study highlighted the value of using multipoint tailings discharge locations to develop extensive beaches across the full embankment perimeter, so as to ensure that supernatant water is as far from all points of the embankment as possible.

4. DISCUSSION AND CONCLUSIONS

Dam breach and inundation studies are an important aspect of dam safety procedures, and all efforts should be made to produce conservative yet credible results for the protection of the public and the downstream environment. However, inundation results based on unrealistic modes of failure do not offer any real value to the owner, regulators, or the public, because they provide little insight into the actual risk posed by the facility. A major difficulty with dam breach assessments is due to the considerable uncertainty involved in each step of the analysis. This situation, combined with the lack of any standardized or mandated approach for completing such analyses, leads to the need for the practitioners to make assumptions and choices that may substantially impact the modelled results. Practitioners must rely on good professional judgement and experience when carrying out and interpreting their work. Furthermore, simply applying an empirical relationship can result in unrealistic or impossible results, and physical constraints need to be considered throughout the process (e.g. mixing too high of a solids content with free water may result in a non-flowable tailings mass). It is important that all dam breach modelling results be viewed in this context.

The major benefit of dam breach studies, no matter how improbable the results may be, is that they trigger discussions on various possible measures to reduce the risk of a breach. One possible measure includes reduction of pore water from the tailings mass, which can improve the rheological characteristics so that the stored tailings solids are non-flowable as described by Adams et al (2017). Another measure that seems to be frequently evaluated in the post Mount Polley and Samarco era is related to the size of the supernatant pond. The current trends are to reduce the supernatant pond size to the extent practicable, while considering the geochemical and climate constraints for each project, as it is recognized that large ponds can increase the risk of breaches and the extent of downstream impacts. For each of the presented case studies, it was the large volume of water in the TSF that exaggerated the downstream inundation extent. In the recent Mount Polley tailings dam breach incident, it has been acknowledged that the foundation failure of the dam would have resulted in a dam crest deformation and potentially some tailings slumping, but not in a catastrophic breach and release of the stored TSF content, which would not occur if the tailings beaches were adequately developed and the facility had less stored water (KCB 2015). It was the overtopping and discharge of supernatant pond in the deformed crest area that led to the downcutting of the embankment and the subsequent massive release of water and tailings solids. The reduction of stored water, along with sound construction and operational practices, followed by good closure and reclamation measures, all contribute to minimizing the potential risk that TSF embankments pose to society and the environment.

5. ACKNOWLEDGEMENTS

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FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R21

Dam Breach Analysis

Table of Contents

Chapter R21 – Dam Breach Analysis

R21.1 Introduction

Dam breach analyses are used to estimate the potential hazards associated with a failure of a project structure/feature. Dam breach inundation analyses include the following elements: estimation of the dam breach parameters, estimation of the dam breach outflow hydrograph; routing of the dam breach hydrograph downstream; and estimation of downstream inundation extent and severity.

Dam breach prediction models are used to estimate the geometry and formation time of a dam breach. Typically, dam breach prediction models are based on empirical data derived from a number of mostly earth and rockfill dam failures case studies. The available empirical equations relate the dam breach parameters to properties of the dam and reservoir such as height, dam type and its erodibility, volume impounded, and shape of the reservoir.

The most common methods of dam breach outflow hydrograph routing are either one-dimensional or two-dimensional with the latter used when higher levels of accuracy are required or for non-channelized flow situations. For most dam breach analyses, one-dimensional computer software is used. Geographic Information Systems (GIS) are the current state-of-practice for inundation mapping, especially if the dam breach analysis involves populated areas and/or other high potential consequences areas.

The methodologies described in these guidelines are intended to highlight the current state-of-practice tools available to the qualified engineer experienced in hydrology and hydraulics. It remains incumbent on the engineer to exercise sound engineering judgment in selecting the appropriate dam breach analysis type and the required level of detail in modeling and inundation mapping to ensure that they are commensurate with the anticipated consequences, as well as consider how the study results can best be used to aid in determining consequences for a risk-informed decision. Sensitivity analyses for those dam breach analyses with significant impacts are almost always necessary to evaluate the results over the range of credibly possible input parameters. All studies submitted to the FERC should contain a summary of the design assumptions, design analyses, and methodologies used.

R21.2 Dam Breach Analysis Purpose

In the context of risk informed decision making, dam breach analyses are needed for determining the potential consequences of a failure mode's occurrence over a range of loading conditions. It can also be used as part of a dam's remedial design process in the selection of alternatives. The type of analysis as well as the level of accuracy required by the results must be scalable to the potential hazards and complexity of the downstream area being modeled. For risk informed decision making, the dam breach parameters are based on best estimates from similar case studies considering the range of possible values associated with the potential failure mode's specifics and the dam's characteristics.

The results of dam breach analyses are typically tabulated in spreadsheet form and plotted on inundation maps of sufficient detail to understand the potential consequences associated with life loss and economics. These can then be used to formulate estimates of the potential for loss of human life and the economic impacts of resulting damages; however, analysis of social and environmental impacts, damage to national security installations, and political and legal ramifications (which are not easily evaluated and are based on subjective or qualitative evaluation) may be required.

R21.3 Levels of Risk - Scalability

The degree of study and evaluation required to sufficiently define the impacts of dam failure will vary with the extent of existing and potential downstream development, the size of reservoir (depth and storage volume), type of dam, and purpose of the study. Evaluation of the river reach and areas impacted by a dam failure should proceed until sufficient information is generated to reach a sound decision or there is a good understanding of the consequences of failure. To ensure that the proposed study's purpose is accomplished, scalability requirements should also be addressed prior to commencing a dam breach study in a scoping meeting. This discussion should also include sensitivity analyses to address uncertainty. A tiered approach to scalability is outlined in Table 1 that generalizes the different levels of analysis required for each tier. Since the anticipated consequences dictate the level of effort, the levels used should be adjusted as needed for the specifics of the study's purpose.

For screening level consequence estimation, for a dam with little uncertainty in the possible impacts, it could be the case that the existing dam breach models are sufficient. For most other more in-depth analyses new models will need to be run for a particular failure mode. This should be discussed during the scoping meeting discussed above.

Table R21-1: Generalized Scalability for Dam Breach Analysis

Level of Effort	Breach parameter and hydrograph estimation	Computational Methods	Breach Hydrograph Routing	Dam Breach Analysis Output
Screening	Empirical equations or Table 1 from Appendix A of Chapter 2 (FERC, 1993)	SMPDBRK, HEC-1, HEC-HMS, SITES/WinDamB, HEC-RAS	Steady-state Or Hydrologic Routing	Table of critical cross-sections
Typical	Empirical equations or physically based models	Combination or exclusively HEC-RAS and SITES/ WinDamB	Unsteady-State	Table of critical cross-sections, Inundation maps with USGS or GIS base maps
Advanced	Empirical equations, physically based models, or probabilistic approach using a Monte Carlo analysis to determine the dam breach parameters	Combination or exclusively FLO2D, Mike 21 (computational fluid dynamics) for non-channelized areas and HEC-RAS for lower consequences, well channelized areas	Unsteady-State	High resolution GIS base maps created from high resolution survey data

R21.4 Dam Breach Analysis Modeling

Although not an exhaustive discussion, some of the primary considerations in creating the dam breach analysis model are discussed in the following sections.

R21.4.1 Dam Breach Parameter Estimation

Methods used for estimating dam breach hydrographs require selecting the size, shape, and time of breach development to its final dimensions. It is important to note that depending on the type of computer modeling, the treatment of breach development time may be different from the case studies. The shape of the peak breach outflow hydrograph is influenced by the storage in the impoundment at the time of breach, reservoir inflow at the time of breach, size of the dam, and most importantly, the dam type's erodibility and/or mode of assumed failure. For instance, a brittle concrete or structural failure will have a much faster time of breach development as compared to an overtopping failure of a large, cohesive, well compacted, and well vegetated embankment. Since the outflow hydrograph can vary widely depending upon these factors, careful consideration of the dam breach modeling inputs should be agreed upon by the risk team (licensee, consultants, and regulator) prior to commencing the study. Ideally, dam breach analyses should be performed for a specific failure mode, so the breach scenario may be well-understood. For example, if the impacts from a potential failure of a tainter gate are being studied, then breach dimensions would be limited to the dimensions of the gate and the failure mechanism would be based on the potential failure mode. -The breach parameter estimation should strive for realistic assumptions so that the modeling output is useful to risk informed decision making.

For modeling dam breaches associated with structural failure that results in a rapid removal of the project feature, many of these assumptions are straightforward. Potential overtopping and piping failures are more difficult and require the use of empirically based or probabilistic methods. Empirical dam breach parameters are assumed based on comparisons to similar dam failure case studies. For quick and conservative screening or preliminary applications, see Chapter 2 E.3 – Appendix C, Table 1.

The four most widely used and accepted empirically derived enveloping curves and/or equations for predicting breach parameters are: MacDonald & Langridge – Monopolis (1984), USBR (1988), Von Thun and Gillette (1990), and Froehlich (1995a, 1995b, 2008). These methods have reasonably good correlation when comparing predicted values to actual observed values. There are also computer models based on laboratory testing for the breach development such as NWS BREACH, NRCS SITES and WinDamB that can be used as well for the breach prediction process.

Still, the inherent uncertainty in breach parameter estimation should not be overlooked. Historically, this uncertainty was evaluated by running a range of possible breach parameter sets in a sensitivity analysis, to understand the full range of possible dam breach outcomes, and how sensitive those outcomes were to the range of inputs.

In support of risk informed decision making, a probabilistic approach to dam breach modeling may be considered. A probabilistic dam breach parameter evaluation requires the investigator to assign a probability density function (PDF) to each of the uncertain breach parameters. The PDF could be a simple uniform distribution (for example, the piping initiation elevation, where all elevations might be equally probable), or a more common normal (Gaussian) distribution. By examining the breach parameter predictive equations that apply to the subject dam, understanding probable failure modes and site conditions, and using sound engineering judgment, means and variances can be approximated to define the PDFs.

Once the PDFs are assigned, breach parameters are randomly sampled about those predefined distributions, to assemble a breach parameter set. Each set is run through the dam breach model as a single modeled event called a “realization”, and the resulting peak of the breach outflow hydrograph is stored. This procedure is repeated using a Monte Carlo Approach until statistical convergence is achieved in the results (i.e. the mean and standard deviation of the population set of possible outcomes ceases to change with successive realizations). The population set of breach outflow peaks is then ordered and ranked, and each value is assigned an exceedance probability. This then allows the investigator to prepare exceedance probability inundation maps, rather than static deterministic inundation maps. A simple example of an exceedance probability inundation map is shown in Figure 1 below.

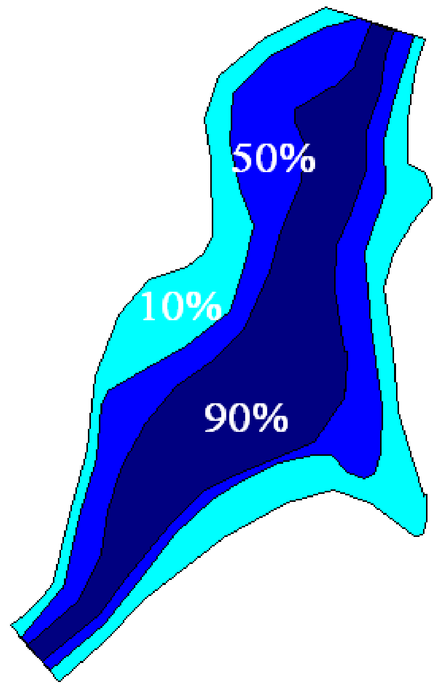

Figure R21-1. Exceedance Probability Inundation Map.

Because of the complexity of this type of analysis, and the large number of realizations required for statistical convergence, the investigator will require significant modeling experience to ensure the dam breach model is efficient and stable over a wide range of breach scenarios. In addition, a basic level of programming experience will help to set up a batch mode run of the dam breach model. More information on probabilistic dam breach modeling can be found in Goodell (2012), Froehlich and Goodell (2012), Froehlich (2008) and Wahl (2004).

Additional information regarding dam breach parameter estimation can be found in Section E.3- Appendix C.

R21.4.2 Dam Breach Model Type

Models to route the flood can be one- or two-dimensional, or can be a combination of both. In general, as the flood plain widens or becomes non-channelized, one-dimensional analysis becomes less reliable. The most commonly used models for estimating both the dam breach outflow hydrograph and routing it downstream are parametric models (HEC-1, HEC-HMS, HEC-RAS, BOSS DAMBRK, FLO 2D, and Mike 21). *Note that the NWS no longer supports DAMBRK and FLDWAV and thus, these computer software programs are not recommended by FERC.* Parametric models can be either hydrologic or hydraulic.

Hydrologic routing programs, such as HEC-1 or HEC-HMS, solve the continuity equation and an analytical or an empirical relationship between storage within the reach and discharge at the model's downstream end. Although they do not account for significant backwater effects, the hydrologic routing models offer the advantages of simplicity, ease of use and computational efficiency. Hydrologic routing models provide attenuated flow hydrographs at locations of interest, but do not provide accurate information on water surface elevations or flow velocities. Also referred to as storage routing, one-dimensional modeling is performed for steady flow conditions ignoring the pressure and acceleration contributions to the total momentum force. Hydrologic routing is typically used in screening level applications.

For most dam breach analyses applications, the recommended method and current state-of-practice involves unsteady flow and dynamic routing. This is known as transient flow or hydraulic routing and is used to predict dam breach wave formation and model downstream progression. The hydraulic routing methods solve and therefore account for the essential momentum forces involved in the rapidly changing flow caused by a dam breach.

For the same outflow hydrograph, the storage or hydrologic routing will usually yields greater attenuation which produces lower discharges and stages downstream than hydraulic or transient flow routing.

R21.4.3 Downstream Floodplain Modeling

Generally speaking, there are two different approaches to simulate the flood inundation caused by a dam breach: one-dimensional (1-D) and two-dimensional (2-D).

Note: Although three dimensional modeling exists, it is not typically used in dam safety practice for dam break modeling.

R21.4.3.1 One-Dimensional Modeling

The 1-D approach to flood inundation modeling only considers one dimension of the flood flow in the direction of x axis (the downstream direction). The unidirectional flow is best represented by the St. Venant formula used for calculating the 1-D flow of the flood wave. Typical modeling software used for calculating the one-dimensional flood flows would include HEC-RAS, and Mike 11 HD.

The modeling of the downstream river conditions in the event of a dam failure using 1-D models requires knowledge of the lateral and longitudinal geometry of the stream and its frictional resistance. This determines how the peak of the flood wave is reduced as it moves downstream (attenuation), the travel time of the flood peak between points of interest, the maximum water stage at points of interest, and the change in shape of the hydrograph as it moves downstream. These effects are governed by factors such as: the channel bedslope; the cross-sectional area and geometry of the main channel, overbank, and backwater areas; the roughness of the main channel and overbank; the existence of storage of floodwaters in off-channel areas from active water conveyance areas; the shape of the flood hydrograph as it enters the channel reach, and the computational solution scheme.

Depending on the level of detail required by the study, field surveys may be needed to verify selected routing parameters and details such as the Manning's number, ineffective flow and overbank areas, bridge constrictions, and off-channel storage. Often a discharge relationship must be obtained for any downstream dams or flow control structures (inline structures). In some cases, some of this information can be obtained from a review of aerial photographs, Flood Insurance Rating Maps, and recent topographic maps.

Depending on scalability requirements, the downstream cross-sectional geometry can be obtained from 10m Digital Elevation Models or topographic maps. In populated areas that introduce high levels of uncertainty, higher quality LiDAR data or actual field surveys may be needed. Field verification should be performed at all cross-sections in the downstream reach where critical information is needed. Also, 10m DEMs and LiDAR do not contain bathymetric data and may have to be augmented by hydrosurveys to obtain riverbed information.

R21.4.3.2 Two-Dimensional Modeling

In the 2-D approach, there are no cross-sections, as with 1-D modeling. Instead, the riverbed is defined by a network field, single grids or mesh, in which the shape can be square (cell based with regular elevation intervals) or polygonal (with irregular intervals) where each individual element has an associated elevation. The single grid has square fields (cells) with constant size, for example, 10 x 10 meters. The flexible mesh has an irregular representation that can be square, rectangular, triangular, or a combination of these shapes; also, the size of the shapes can vary. Typical modeling software used for calculating two-dimensional flood flows would include FLO-2D, Mike 21 HD, Mike Flood (and HEC-RAS version 5.0 which is due end of CY 2013).

Within the 2-D computer model, water propagates by a cell to cell evaluation basis. In contrast to the 1-D model, the Manning coefficient can be variable and applied at every element location (cell). For example, if the element sizes are 5 x 5 meters, and if some elements have dense foliage, where others not, it is possible to define different Manning coefficients for the separate elements at as much as a 5 x 5 meter interval.

The 2-D modeling method is not constrained by the same limitations as the 1-D approach. The limitation to a horizontal water surface at the cross-section locations and the lack of exchange of momentum between the main channels and flooded areas, doesn't exist in the 2-D approach. Although the water surface is horizontal within an individual cell, when propagating from cell to cell along a cross-section, the water surface can oscillate according to the dynamics of the model. Also, the exchange of impulses between cells is possible, and therefore, the momentum exchange between the main channel and the flood area is possible.

R21.4.4 Boundary Conditions

Boundary conditions both at the upstream and downstream ends of the model are needed in flood routing. Their selection is dependent on the dam breach study's purpose, their locations relative to the area(s) of interest, and level of sensitivity dependent on the degree of confidence required.

The upstream boundary condition can be defined by a stage-storage relationship, or as a series of cross-sections cut through the reservoir. The method selected normally depends on the shape of the reservoir. Long, riverine reservoirs with relatively fast breach development times should be modeled using bathymetric data and cross sections (dynamic reservoir routing) to account for the hydraulic losses as water in upper portions of the reservoir travels to the dam breach. Dynamic routing is also required when the hydraulic slope of the reservoir is significant and low reservoir rim areas could potentially impact the study results. In larger volume, more compact impoundments, with relatively slow breach development times, where travel time through the reservoir is not critical, the stage-storage method (level pool reservoir routing) requires less effort and has the benefit of accurately modeling the actual storage within the reservoir based on known relationships. Selecting the appropriate reservoir drawdown approach (dynamic or level pool) can be a very important part of the dam breach study. Level pool can save significant time and effort, but if used inappropriately, can greatly overestimate the breach hydrograph.

The assumptions used for the initial reservoir water surface can either be specific to the failure mode being studied, consider a range of possible elevations or annual exceedance probabilities, or for preliminary or screening applications begin with the reservoir at the normal maximum pool elevation especially if there is no allocated or planned flood control storage (e.g. run-of-river). In risk informed decision making, the best estimate should be used for the dam breach scenario being evaluated.

As discussed in the following section, the downstream boundary conditions are not usually an important assumption because routing for risk informed decision making should be continued far enough downstream where impacts are no longer significant. This point could occur when:

- There are no habitable structures, and anticipated future development in the floodplain is limited,
- Flood flows are contained within a large downstream reservoir,
- Flood flows are confined within the downstream channel, or
- Flood flows enter a bay or ocean.

Additional information regarding dam breach parameter estimation can be found in Chapter 2 Section E.3 of Appendix C.

R21.4.5 Inflow hydrograph, project discharge and concurrent flows

The inflow hydrograph is a straightforward assumption used in the model that is defined by the study's purpose. In risk informed decision making, a range of inflows is usually considered in the analysis. The same can be said of the baseflow condition assumed in the river reach being studied.

The dam's spillway and/or project discharge operations should be modeled as most realistically anticipated for the study's purpose. Debris loading or other spillway blockage situations may require artificially modifying the dam breach model's project discharge rating curve to compensate for the diminished spillway capacity. Gate operations should be modeled depending on normal and flood operation procedures in place at the project, or as described in the failure mode being investigated.

When routing a dam breach flood wave through the downstream floodplain, appropriate local inflows should be considered in the computations, as concurrent floods in a river system may increase the area flooded and also alter the flow velocity and depth of flow as well as the rate of rise of flood flows. These assumptions ultimately affect the estimation of downstream consequences and the level of effort in determining these assumptions should be requisite to the level of detail required and include sensitivities as appropriate. This is an important issue that should be discussed in the scoping phase of the modeling process, so that all the parties are agreed on what assumptions are reasonable.

If historical records are available and the records indicate that the downstream tributaries are characteristically in flood stage at the same time, then concurrent inflows based on historical records should be adjusted so they are compatible with the magnitude of the flood inflow computed for the dam under study. For screening level and sunny-day EAP inundation mapping dam breach applications, the concurrent inflows may be assumed equal to the mean annual flood (approximately bankfull capacity) for the channel and tributaries downstream from the dam. The mean annual flood can be determined from flood flow frequency studies. As the distance downstream from the dam increases, engineering judgment may be required to adjust the concurrent inflows selected.

R21.4.6 Domino Failure Consideration

The possibility of a domino-like failure of downstream dam(s) resulting in a cumulative flood wave large enough to cause adverse impacts should be considered. If one or more dams are located downstream of the dam site under review, the dam breach failure wave should be routed downstream to determine if any of the downstream dams would breach in a domino-like action. While the flood routing of inflows through the dam being studied may be either dynamic or level pool, the routing through all subsequent downstream reservoirs should be dynamic. Tailwater elevations should consider the effect of backwater from downstream constrictions.

Much like concurrent flows, described above in section 5.5, the introduction of downstream dam(s) to the model creates the need for numerous additional variables. If the downstream dam(s) is managed by a different entity than the one performing the dam breach analysis, these variables could be hard to estimate without consultation. This is an important issue that should be discussed in the scoping phase of the modeling process, so that all the parties are agreed on what assumptions are reasonable.

R21.5 Dam Breach Output

The output of the dam breach model for use in risk analysis should be in digital format, such as GIS. There are very few situations where a hand drawn inundation map on a topographic quadrangle map will be acceptable for decision making. The expected outputs from a dam failure analysis for each flood routing are the inundation polygon, the analyzed cross sections and their output data (water surface elevations, hydrograph timing, velocity), and for consequence estimation a grid of the Depth-Velocity of the breach outflow.

R21.6 Accounting for Uncertainty

Analyses of dam failures are complex with many historical dam failures not completely understood. Accounting for uncertainties may not be needed in situations where it can be shown that the complete and sudden removal of the dam would not endanger human life or cause extensive property damage. The principal uncertainties in determining outflow from a dam failure involve the potential failure mode and the selection of the breach size, shape, and time of formation as input parameters for the computations. Uncertainly also exists in the selected flood routing methodology and model input data, concurrent flow estimation, and how reservoir sedimentation may behave during a dam failure. Uncertainty is most often accounted for by performing a sensitivity analysis over a range of best estimates for dam breach modeling input parameters. However, to fully support risk informed decision making, quantification of the uncertainties is required in the outcomes. Quantification of uncertainty requires a probabilistic analysis of the uncertain input parameters; most notably the dam breach parameters, and an exceedance probability index for the full range of possible breach outflow hydrographs. This procedure is introduced in Section R21.5.1, Dam Breach Parameter Estimation.

One of the goals of the pre-analysis scoping meeting is to discuss the range of selected parameters studied and methodology used, and what is the inherent uncertainty of each. A well written account of the uncertainty should include the best estimate of the parameter, the sensitivity of the study to variation in the parameter, an estimate or study of the variation of the parameter, a discussion of how uncertainty has been reduced to the extent practicable, and, if necessary, where future efforts should be focused to further reduce uncertainty.

R21.7 References

R21 – Appendix A – Definitions

Annual Exceedance Probability - The estimated probability that an event (such as a flood) of specified magnitude will be equaled or exceeded in any year.

Dam Failure Inundation Map - A cartographic map depicting the area downstream from a dam that-is predicted to be flooded in the event of a failure of the dam.

Hazard potential classification - The hazard potential of a dam pertains to the potential for loss of human life or property damage in the area downstream of the dam in the event of failure or incorrect operation of a dam. Hazard potential does not refer to the structural integrity of the dam itself, but rather the effects if a failure should occur.

Flood Routing - A process of progressively determining over time the amplitude and speed of a flood wave as it moves past a dam and continues downstream to successive points along a river or stream.

Hazard - A situation which creates the potential for adverse consequences such as loss of life, property damage, or an unexpected or unpredictable event. Adverse impacts in the area downstream of a dam are the impacts resulting from flood waters released through spillways and outlet works or by partial or complete failure of the dam. There may also be impacts upstream of the dam due to backwater flooding or landslides around the reservoir perimeter.

Hydrograph - A graphical representation of the stream flow stage or discharge as a function of time at a particular point on a watercourse.

Incremental Impact Assessment - An assessment of the impacts caused by the increase in flooding due to the failure of a dam or other water impounding structure under a specific flow condition. This assessment evaluates the impacts caused by the passage of a specific flow condition without a dam failure and then considers the same flow condition with a dam failure. The incremental impacts between the non-breach and breach cases on downstream life and property are identified and evaluated.

Outlet Works – An appurtenance in a dam, other than a spillway, that is used to release water (generally controlled) from a reservoir.

Probable Maximum Flood (PMF) - The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study.

Reservoir Regulation Procedure (Rule Curve) - Compilation of operating procedures that govern reservoir storage and releases.

Spillway - A gated or ungated hydraulic overflow structure used to discharge water from a reservoir. Below are several common spillway types:

- **Service Spillway**. A spillway that is designed to provide continuous or frequent regulated or unregulated releases from a reservoir without significant damage to either the dam or its appurtenant structures.

- **Auxiliary Spillway**. Any secondary spillway which is designed to be operated very infrequently; possibly, some degree of structural damage or erosion to the spillway would occur during operation.

- **Emergency Spillway**. A spillway that is designed to provide additional protection against overtopping of dams and is intended for use under extreme flood conditions or mis-operation or malfunction of the service spillway.

Spillway Capacity - The maximum amount of flow a spillway section can pass when the reservoir water level is at the design maximum pool elevation or dam crest elevation.

POLYMET
MINING

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Water Modeling Data Package
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Large Table 23 Annual Summary of Concentration Statistics for the WWTP Reject Concentrate

Constituent	Mine Year		1			5			11			14			20			25		
	Percentile		Avg P10[1]	Avg P50[2]	Avg P90[3]	Avg P10[1]	Avg P50[2]	Avg P90[3]	Avg P10[1]	Avg P50[2]	Avg P90[3]	Avg P10[1]	Avg P50[2]	Avg P90[3]	Avg P10[1]	Avg P50[2]	Avg P90[3]	Avg P10[1]	Avg P50[2]	Avg P90[3]
	Units	Modeled WWTF Target																		
Ag (Silver)	µg/L	1	1.10E-01	1.10E-01	1.10E-01	1.50E-01	1.50E-01	1.50E-01	1.77E-01	1.90E-01	2.03E-01	1.77E-01	1.90E-01	2.03E-01	1.80E-01	1.80E-01	1.80E-01	1.38E-01	1.50E-01	1.63E-01
Al (Aluminum)	µg/L	125	1.11E+01	1.17E+01	1.23E+01	1.13E+01	1.20E+01	1.27E+01	3.61E+00	5.10E+00	6.60E+00	4.74E+00	7.06E+00	9.79E+00	1.63E+00	2.35E+00	3.00E+00	5.25E+00	7.74E+00	9.99E+00
Alkalinity	mg/L	--	3.13E+03	3.18E+03	3.22E+03	2.50E+03	2.57E+03	2.63E+03	6.18E+01	7.25E+01	8.25E+01	7.42E+01	1.37E+02	1.96E+02	4.45E+01	4.92E+01	5.36E+01	8.11E+01	1.44E+02	2.12E+02
As (Arsenic)	µg/L	10	3.95E+00	4.06E+00	4.16E+00	4.60E+00	5.84E+00	7.08E+00	1.44E+02	2.33E+02	3.31E+02	2.78E+02	4.15E+02	5.58E+02	9.73E+02	1.06E+03	1.15E+03	5.25E+02	6.15E+02	7.03E+02
B (Boron)	µg/L	500	2.67E+02	2.72E+02	2.76E+02	2.74E+02	2.82E+02	2.89E+02	1.41E+02	1.59E+02	1.76E+02	1.66E+02	1.99E+02	2.31E+02	1.02E+02	1.06E+02	1.10E+02	1.43E+02	1.83E+02	2.20E+02
Ba (Barium)	µg/L	2000	3.49E+03	3.51E+03	3.52E+03	2.82E+03	2.84E+03	2.86E+03	3.87E+02	4.00E+02	4.14E+02	3.95E+02	4.17E+02	4.39E+02	2.83E+02	3.01E+02	3.18E+02	2.78E+02	3.01E+02	3.24E+02
Be (Beryllium)	µg/L	4	2.30E-01	2.30E-01	2.30E-01	2.67E-01	2.80E-01	2.92E-01	3.97E-01	4.10E-01	4.23E-01	4.11E-01	4.50E-01	4.89E-01	3.68E-01	3.80E-01	3.93E-01	3.48E-01	4.03E-01	4.53E-01
Ca (Calcium)	mg/L	--	1.23E+02	1.46E+02	1.67E+02	2.79E+02	4.59E+02	6.49E+02	6.92E+02	9.19E+02	1.16E+03	1.15E+03	1.54E+03	1.95E+03	2.43E+03	3.74E+03	5.00E+03	2.19E+03	2.95E+03	3.77E+03
Cd (Cadmium)	µg/L	4	1.20E-01	1.20E-01	1.20E-01	1.86E-01	2.50E-01	3.13E-01	4.48E-01	7.89E-01	1.14E+00	6.61E-01	1.02E+00	1.39E+00	9.28E-01	1.64E+00	2.42E+00	6.14E-01	1.04E+00	1.44E+00
Cl (Chloride)	mg/L	230	3.68E+02	3.76E+02	3.84E+02	3.81E+02	3.88E+02	3.95E+02	3.52E+02	4.06E+02	4.59E+02	3.67E+02	4.07E+02	4.50E+02	4.38E+02	4.96E+02	5.50E+02	3.29E+02	3.73E+02	4.16E+02
Co (Cobalt)	µg/L	5	1.58E+00	2.02E+00	2.49E+00	2.19E+01	5.78E+01	9.80E+01	1.03E+02	2.39E+02	3.75E+02	1.36E+02	2.88E+02	4.59E+02	2.59E+02	5.36E+02	8.47E+02	1.70E+02	3.91E+02	6.02E+02
Cr (Chromium)	µg/L	11	4.66E-01	4.90E-01	5.16E-01	9.41E-01	1.03E+00	1.12E+00	5.16E+00	5.78E+00	6.32E+00	5.23E+00	6.07E+00	6.99E+00	6.75E+00	7.15E+00	7.55E+00	4.56E+00	5.03E+00	5.48E+00
Cu (Copper)	µg/L	30	3.60E+00	5.25E+00	6.99E+00	2.23E+02	4.15E+02	5.96E+02	3.95E+03	6.19E+03	8.28E+03	4.87E+03	7.37E+03	9.86E+03	6.01E+03	8.83E+03	1.16E+04	3.65E+03	5.67E+03	7.83E+03
F (Fluoride)	mg/L	2	7.33E+01	7.37E+01	7.42E+01	6.62E+01	6.79E+01	6.96E+01	1.98E+01	2.22E+01	2.46E+01	1.60E+01	1.95E+01	2.30E+01	2.17E+01	2.40E+01	2.64E+01	1.23E+01	1.38E+01	1.53E+01
Fe (Iron)	µg/L	300	3.39E+04	3.46E+04	3.54E+04	5.99E+04	6.16E+04	6.34E+04	1.96E+04	2.44E+04	2.94E+04	1.98E+04	3.06E+04	4.08E+04	1.68E+02	2.14E+02	2.63E+02	1.07E+04	2.04E+04	2.99E+04
K (Potassium)	mg/L	--	1.64E+02	1.68E+02	1.72E+02	2.01E+02	2.11E+02	2.21E+02	3.27E+02	3.85E+02	4.39E+02	4.04E+02	4.77E+02	5.49E+02	7.02E+02	7.32E+02	7.62E+02	5.05E+02	5.42E+02	5.80E+02
Mg (Magnesium)	mg/L	--	1.25E+03	1.28E+03	1.31E+03	1.45E+03	1.53E+03	1.60E+03	1.20E+03	1.37E+03	1.53E+03	1.44E+03	1.66E+03	1.89E+03	1.42E+03	1.64E+03	1.88E+03	1.56E+03	1.88E+03	2.21E+03
Mn (Manganese)	µg/L	50	3.88E+03	4.06E+03	4.25E+03	6.52E+03	7.08E+03	7.71E+03	8.90E+03	1.14E+04	1.41E+04	1.00E+04	1.33E+04	1.66E+04	7.30E+03	1.08E+04	1.42E+04	9.00E+03	1.21E+04	1.53E+04
Na (Sodium)	mg/L	--	1.23E+03	1.25E+03	1.26E+03	1.25E+03	1.30E+03	1.37E+03	1.14E+03	1.24E+03	1.34E+03	1.21E+03	1.32E+03	1.42E+03	1.84E+03	2.01E+03	2.19E+03	1.26E+03	1.39E+03	1.52E+03
Ni (Nickel)	µg/L	100	5.12E+00	8.65E+00	1.23E+01	2.44E+02	8.26E+02	1.48E+03	1.89E+03	4.08E+03	6.59E+03	2.43E+03	4.60E+03	6.59E+03	4.19E+03	8.79E+03	1.37E+04	3.01E+03	6.11E+03	9.05E+03
Pb (Lead)	µg/L	19	1.17E+00	1.18E+00	1.19E+00	1.51E+00	1.64E+00	1.77E+00	3.25E+02	4.96E+02	6.51E+02	5.11E+02	7.22E+02	9.44E+02	1.12E+03	1.21E+03	1.29E+03	6.40E+02	7.32E+02	8.23E+02
Sb (Antimony)	µg/L	31	3.51E-01	4.69E-01	5.84E-01	1.08E+00	2.18E+00	3.21E+00	6.04E+00	7.38E+00	8.73E+00	7.37E+00	8.95E+00	1.05E+01	1.45E+01	1.75E+01	2.03E+01	8.79E+00	1.07E+01	1.26E+01
Se (Selenium)	µg/L	5	5.17E-01	5.30E-01	5.43E-01	6.64E-01	6.90E-01	7.14E-01	1.51E+00	1.80E+00	2.08E+00	1.94E+00	2.30E+00	2.65E+00	3.86E+00	5.29E+00	6.60E+00	2.70E+00	3.33E+00	3.96E+00
SO4 (Sulfate)	mg/L	250	3.86E+03	3.91E+03	3.96E+03	5.63E+03	5.84E+03	6.05E+03	4.91E+03	5.27E+03	5.64E+03	5.50E+03	6.00E+03	6.51E+03	6.61E+03	7.39E+03	8.23E+03	5.67E+03	6.53E+03	7.47E+03
Tl (Thallium)	µg/L	0.56	1.50E-01	1.50E-01	1.50E-01	1.60E-01	1.60E-01	1.60E-01	1.47E-01	1.60E-01	1.73E-01	1.44E-01	1.69E-01	1.95E-01	1.68E-01	1.80E-01	1.93E-01	1.28E-01	1.40E-01	1.53E-01
V (Vanadium)	µg/L	50	3.87E+00	3.97E+00	4.08E+00	4.18E+00	4.28E+00	4.41E+00	6.79E+00	7.54E+00	8.32E+00	7.09E+00	8.04E+00	9.11E+00	8.90E+00	9.15E+00	9.39E+00	6.11E+00	6.57E+00	7.04E+00
Zn (Zinc)	µg/L	388	1.04E+01	1.07E+01	1.10E+01	1.44E+01	1.77E+01	2.09E+01	4.83E+01	6.57E+01	8.24E+01	6.74E+01	8.47E+01	1.02E+02	2.49E+02	8.73E+02	1.56E+03	6.09E+01	8.56E+01	1.10E+02

Notes

[1] Values shown are the average of the monthly P10 values for the referenced Mine Year.

[2] Values shown are the average of the monthly P50 values for the referenced Mine Year.

[3] Values shown are the average of the monthly P90 values for the referenced Mine Year.

2.00E+02 Values below the modeled WWTF effluent target are shown in bold with light blue shading.

[MPARS] DNR Request for Comments - Dam Safety - Construction - St. Louis County - Applications 2016-1383 and 2016-1380

2016-1383
Fisheries' concern about the Hydrometallurgical Facility (HRF) is because it will hold waste from the metallurgical plant and will be dependent on a liner underneath and a wick drain system. This seems like it would function appropriately during operation of the mine and certainly our engineers and hydrologists have this covered for the review.

My concern is about far into the future. How long does such a liner last and what happens when it inevitably degrades as nothing lasts forever? Even if it takes 200 years, the waste will still be there and in its location would be very susceptible to leaching into nearby wetlands and groundwater. There is no mention of the expected longevity of the liner and leakage system in the long term closure description. There is mention of a monitoring plan but no mention of how the liner could be maintained or repaired or replaced. (Section 7.3, Residue Management Plan v.5). I don't understand how a liner could be replaced, or even repaired, under a 97 acre site with 50 feet of fill on top. The site is to be capped for long-term closure, but I don’t know if that means there would be no leaching concerns long-term. I would think not as long as this location has groundwater movement. The Hydrometallurgical Residue Facility is a concern to Fisheries because of its potential impact on water quality as the system ages - on the very long term scale.

2016-1380
The permit for reinforcing and building up the legacy tailings pits is less concerning to fisheries and water quality concerns, I think because the waste being discharged to them would be more dilute and of a different composition. In addition these pits have a storage history and they are designed with a treatment system in place to catch leachate. They are not dependent on a manufactured liner either. As long as our engineers and hydrologists have confidence in the design, I would hope fisheries and water quality are protected.

Edie Evarts | Area Fisheries Supervisor

MN Department of Natural Resources

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June 29, 2017

Chad Konickson, Chief of the St. Paul District Regulatory Branch
Kenton Spading, PolyMet Project Manager
US Army Corps of Engineers
Sibley Square at Mears Park
190 5th Street East, Suite 401
St. Paul, MN 55101-1638

RE: PolyMet Mining Corp. NorthMet Project Clean Water Act Section 404 Permit MVP-1999-5528-JKA
Request for Public Notice, Hearing, and Supplemental Environmental Impact Statement

Dear Mr. Konickson and Mr. Spading:

This letter is submitted on behalf of WaterLegacy. We request that the U.S. Army Corps of Engineers ("USACE") issue a new public notice and schedule a public hearing for the Clean Water Act ("CWA") Section 404 permit for the proposed PolyMet NorthMet copper-nickel mining project ("PolyMet Project"). This request is made pursuant to the Clean Water Act, 33 U.S.C. §1344(a) and implementing federal regulations in Part 327 of Title 33 of the Code of Federal Regulations. There are substantial issues and valid interests supporting a hearing, and requests were made within the applicable notice and comment period.

Based on significant project changes recently proposed and significant new information disclosed by PolyMet in the course of applying for a Minnesota Permit to Mine, Dam Safety Permit and Water Appropriations Permits, WaterLegacy also requests that a supplemental environmental impact statement ("EIS") be required under the National Environmental Policy Act ("NEPA"), 42 U.S.C. §4332(2)(C) and its implementing regulations, 33 C.F.R. § 230.13(b) and 40 C.F.R. §1502.9(c)(1)(ii). Information in the Minnesota state permitting process demonstrates that there are significant new circumstances and new information relevant to environmental concerns and bearing on the proposed action and its impact that requires a supplemental EIS be prepared.

A. Public Notice and Hearing

1. Prior Requests for Public Notice and Hearing

Anticipating the release of the PolyMet NorthMet final environmental impact statement ("FEIS), WaterLegacy requested in June 2014 that the USACE issue a supplemental public notice and hold a public hearing when the environmental review process was completed and the FEIS prepared.[1] The U.S. Environmental Protection Agency ("EPA") in its comments on the supplemental draft EIS for the NorthMet project had stated that PolyMet's August 19, 2013 Section 404 application was not a standalone document and that it relied on environmental review documents to meet requirements for compliance with the Clean Water Act.[2]

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[1] WaterLegacy letter to USACE, June 16, 2014 (Attachment A).
[2] U.S. EPA Comments on PolyMet NorthMet supplemental draft EIS, Mar. 13, 2014 (Attachment B).

The USACE issued a public notice for the PolyMet Project on November 13, 2015, which stated that it was based on PolyMet's August 19, 2013 Section 404 application and PolyMet's request to modify the application to include the discharge of fill material into an additional 1.37 acres of wetlands. The USACE and other agencies provided a comment period through December 14, 2015 on the Section 404 permit application and the FEIS for the PolyMet Project.[3]

On November 19, 2015, within the applicable comment period, WaterLegacy joined with other Minnesota Environmental Partnership groups in requesting a public hearing based not only on the small addition in wetlands impacts, but on new information pertinent to the PolyMet Project Section 404 permit contained in the FEIS, upon which the PolyMet application depended.[4]

In response to follow up regarding the USACE's decision whether or not to conduct a public hearing, WaterLegacy received the following email from the USACE on December 18, 2015:

> We did have a public hearing for the purposes of the Clean Water Act Section 404 permit evaluation process on January 16, 2014. At this time, we have not made a determination regarding another public hearing. We have not completed our review of the responses to our public notice of November 13 inviting comments on changes to wetland impacts associated with the proposed project. We will make a decision regarding the need to hold another public hearing once we have assessed the issues raised by the comments.[5]

2. Grounds for Public Notice and Public Hearing

Since December 18, 2015, WaterLegacy has received no written determination from the USACE as to any decision regarding the need to hold a public hearing on the PolyMet Project. Federal regulations require that "Requests for a public hearing under this paragraph shall be granted, unless the district engineer determines that the issues raised are insubstantial or there is otherwise no valid interest to be served by a hearing," and that "The district engineer will make such a determination in writing, and communicate his reasons therefor to all requesting parties." 33 C.F.R. §327.4(b).

The issues raised by Minnesota Environmental Partnership ("MEP") groups, including WaterLegacy, in requesting a public hearing were substantial, pertained to valid and compelling public interests, and addressed matters that had arisen since the time of the hearing on the supplemental draft EIS or for which new factual information had become available since that time. These issues included new concerns regarding water modeling, seepage and containment of contaminated wastewater, cumulative northward flow of pollutants to the Boundary Waters watershed, and the potential application of best available technology to avoid catastrophic tailings dam failure - taking into consideration the Mount Polley tailings dam collapse in Canada and the resulting independent scientific report on best available technology for tailings disposal.

A hearing was also requested on the grounds that neither the August 19, 2013 PolyMet permit application, the FEIS, nor any document in the environmental review record prior to December 14, 2015 provided information needed to determine compliance with Section 404 requirements,

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[3] USACE Public Notice for the PolyMet NorthMet Project, Nov. 13, 2015 (Attachment C).
[4] MEP letter to USACE requesting PolyMet NorthMet hearing, Nov. 19, 2015 (Attachment D).
[5] USACE email to WaterLegacy on PolyMet NorthMet hearing, Dec. 18, 2015 (Attachment E).

including but not limited to a quantitative assessment of the PolyMet Project's indirect impacts on wetlands, a commensurate proposal for compensatory wetlands mitigation, and financial assurance for such secondary wetlands impacts, 33 C.F.R. §§ 332.3(k)(1), 332.3(m), 332.4 (b). Similarly, MEP groups requested a hearing on the grounds that neither the FEIS nor supporting documents identified the least environmentally damaging practicable alternative ("LEDPA") for the Project, as required under 40 C.F.R. §230.10(a).

These grounds are still valid today. A public hearing is required under the Clean Water Act, 33 U.S.C. §1344(a) and under 33 C.F.R., Part 327.

B. Supplemental Environmental Impact Statement

In addition to requesting a hearing based on outstanding concerns since the PolyMet NorthMet FEIS, WaterLegacy requests that the USACE require a supplemental EIS to respond to significant new circumstances and new information that has been disclosed as a result of PolyMet's application for various Minnesota state permits. These new circumstances and new information bear directly upon the jurisdiction of the USACE to require compliance with requirements in Part 230 of Title 40 and Part 332 of Title 33 of the Federal Code of Regulations before approving any permit for discharge of dredge and fill materials under Section 404 of the Clean Water Act.

Federal regulations implementing NEPA require that an agency prepare a supplemental EIS when "There are significant new circumstances or information relevant to environmental concerns and bearing on the proposed action or its impacts." 40 C.F.R. §1502.9(c)(1)(ii). This requirement to prepare a supplemental EIS when there are significant new circumstances or information has been specifically adopted by USACE regulations, which state "A supplement to the draft or final EIS should be prepared whenever required as discussed in 40 CFR 1502.09(c)." 33 C.F.R. § 230.13(b).

The PolyMet Project has changed substantially since the August 2013 PolyMet Section 404 permit application and the November 2015 PolyMet NorthMet FEIS, and significant new information pertinent to the Section 404 permit application has recently come to light.

1. Project Alteration to Remove of Tailings Basin Cement Deep Soil Mixing (CDSM)

The FEIS proposed that cement deep soil mixing ("CDSM") would be used to reduce slope instability and reduce the risk of dam failure, particularly in Cell 2E North Dam of the tailings basin.[6] The current PolyMet proposal proposes to use additional buttresses rather than CDSM, since CDSM, unlike buttresses, would need to be constructed at the start of the project, incurring up front costs to PolyMet.[7] PolyMet's consultants have estimated that this change will result in additional wetlands impacts of approximately 2.97 acres at the tailings basin.[8]

This reliance on buttressing instead of CDSM to provide slope stability may reduce the safety factor for certain liquefaction triggering scenarios. For example, under the liquefaction triggering

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[6] FEIS, available online at http://www.dnr.state.mn.us/input/environmentalreview/polymet/feis-toc.html, 3-4, 3-13, 3-93, 3-105, 3-150, 3-154, 4-437.
[7] Barr, Technical Memorandum, "Tailings Basin Cell 2E North Dam – Modified Buttress as Alternative to Cement Deep Soil Mix Zone," Dec. 30, 2016, p. 1. (Attachment F). The May 2017 NorthMet Dam Safety Permit Application Flotation Tailings Basin eliminates CDSM.
[8] *Id.*, p. 2.

scenario resulting from erosion in cross-section F, the slope stability drops from 1.99 reported in the FEIS, to 1.07 reported in the May 2017 PolyMet Dam Safety Permit Application, a slope stability that is *below* the required factor of safety.[9]

The risk of liquefaction and slope instability as a result of proposed PolyMet wet slurry tailings disposal potentially impacts wetlands and downstream water quality. In addition, the change in proposed engineering to address tailings basin instability affects the assessment of the least environmentally damaging practicable alternative ("LEDPA") for tailings disposal. *See* 40 C.F.R. §230.10(a). WaterLegacy, among other stakeholders, has requested that dry stack tailings best available technology identified in the independent scientific report after Canada's 2014 Mount Polley catastrophic tailings dam collapse be analyzed in environmental review of the PolyMet Project.

PolyMet's slope stability engineering change to reduce its up front capital costs is the type of new circumstance that requires a hard look through a supplemental EIS.

2. Removal of Mine Site Waste Water Treatment Facility (WWTF)

The PolyMet NorthMet FEIS proposed construction of a wastewater treatment facility (WWTF) at the mine site in the first year of mine operation to reduce the level of sulfates, metals and other pollutants before wastewater was piped nine miles to the processing plant. The FEIS proposed that the mine site WWTF would be upgraded to include reverse osmosis or equivalent technology at closure.[10] In addition, the WWTF would assure compliance with water quality standards, since "should water monitoring undertaken during or following operations indicate a need to do so, the WWTF could be expanded or treatment capabilities modified to meet water quality standards."[11]

The WWTF has been integral to the PolyMet NorthMet plan to treat polluted water at the mine site and reject concentrate from the plant site, to treat water from mine site stockpiles, mine pits, the Ore Surge Pile, ancillary mine features and, if necessary, to treat process water from the Overburden Storage and Laydown Area.[12] Starting in year 11, some water from the WWTF would be used to cover East Pit backfill and, then, the combined East Central Pit backfill.[13] Analysis of mine site pollution in the FEIS was calculated assuming treatment at the WWTF and management of mine pit water levels through pumping to and from the WWTF.[14]

The FEIS explained that when the West Pit filled, the WWTF would be upgraded to include reverse osmosis or equivalent technology, and treated effluent from the mine site would be discharged to a wetland flowing toward Dunka Road and eventually into the Partridge River.[15] Treated effluent from the WWTF would be used during closure and post-closure to ensure that

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[9] Compare PolyMet NorthMet FEIS, 5-658, Table 5.2.14-1 with NorthMet Dam Safety Permit Application Flotation Tailings Basin (May 2017), p. 17, Table 3-3. (Attachment G). Complete Dam Safety Application available on line at http://files.dnr.state.mn.us/lands_minerals/northmet/dam-safety/v2/dam_safety_permit_application_flotation_tailings_basin_v2_may2017.pdf

[10] FEIS, 3-52, 3-53.

[11] *Id.*, 3-52, 3-72, 3-75 (Fig. 3.2-17), 3-77 (Fig. 3.2-18), 3-79 (Fig. 3.2-19).

[12] *Id.*, 3-52 to 3-53. There are hundreds of references to the WWTF in the FEIS.

[13] *Id.*, 3-53, 3-64.

[14] *Id.*, 5-117 to 5-118.

[15] *Id.*, 3-65, 3-72, *see* Fig. 5.2.2-10 (Attachment H) for FEIS diagram of WWTF functions.

water levels in the East Pit were sufficient to maintain subaqueous disposal conditions.[16] The water level in the West Pit during closure and post-closure would also be controlled by pumping to the WWTF to prevent untreated surface overflow: "By pumping pit lake water to the WWTF, the pit water level would be managed to always provide sufficient freeboard to absorb extreme precipitation events without overflowing."[17] The FEIS stated the following commitment from PolyMet: "The WWTF would remain operational until water quality monitoring results demonstrate that a non-mechanical system could produce an effluent water quality, which is shown by pilot-testing and modeling, to satisfy water quality-based effluent limits at compliance points without the need for mechanical treatment."[18]

In the process of application to the State of Minnesota for a Permit to Mine and Water Appropriations Permits, PolyMet has recently proposed to eliminate any water treatment at the mine site and build three pipelines to transport high concentration mine pollution as well as less polluted contact water to the plant site.[19] Mine site water equalization basins with untreated contaminated wastewater would be located at a new location south of the Dunka Road, closer to the Partridge River than those proposed in the FEIS, and the construction mine water basin would also be smaller than proposed in the FEIS.[20] Pipelines carrying construction mine water would be routed to the tailings basin.

PolyMet's consultants have stated that the change would reduce direct wetlands impacts by 7.5 acres and that "the Section 404 permit application. . . would be affected by this Project change."[21]

Although PolyMet's consultants may argue otherwise,[22] the removal of the WWTF facility from the PolyMet NorthMet project is a significant new circumstance relevant to environmental concerns and bearing on the proposed action and its impacts. PolyMet's proposal to eliminate the WWTF blandly states that "water quality and rate of the treated discharge to the environment would be the same as were evaluated for the FEIS."[23] However, PolyMet has provided no data and has made no commitments regarding limits on the quantity or concentration of chemical parameters in wastewater (whether treated or untreated) that would be discharged to the Tailings Basin and the East Pit and, thus, to groundwater and to directly connected surface water.[24]

[16] *Id.*, 5-104.
[17] *Id.*, 5-105.
[18] *Id.*, 3-81.
[19] Barr, Technical Memorandum, "Proposed Waste Water Treatment System (WWTS) Relocations (Version 3)," April 11, 2017, p. 1. (Attachment I).
[20] *Id.*, Large Figure 2.
[21] *Id.*, p. 15.
[22] *Id.*, pp. 6-7.
[23] *Id.*, pp. 1, 8. PolyMet also claims that "the quantity, quality, and location" of treated effluent would not change with removal of the WWTF. However, PolyMet's permit applications only identify discharge sites in the vicinity of the tailings basin (Second, Trimble and Unnamed Creek). PolyMet NorthMet Water Appropriations Permit Applications (Apr. 2017) ("Water Approp. Permit App."), pdf pagination ("autop.") 4-59. Complete revised Applications are available online at files.dnr.state.mn.us/lands_minerals/northmet/water-approp/water-appropriation-permit-app-v3.pdf
[24] *Id.* (see entire document).

Although eliminating the mine site WWTF would reduce up front capital costs and might reduce costs during operations,[25] it is highly likely to increase inefficiencies during closure and post-closure, increasing pipeline rupture risks and making adequate long-term water quality treatment less likely. The unavailability of mine site water treatment and the fact that no pipeline would be available until Mine Year 12 to transport treated water back to the East Pit[26] could also interfere with adaptive management options either to cyclically treat East Pit water and reduce contaminant levels or to treat and restore groundwater to the mine site aquifer if needed to mitigate wetlands drawdown impacts.

PolyMet's most recent Water Appropriations Permit Applications claim that the appropriation for Category 1 groundwater containment would only extend through Mine Year 21 and do not illustrate any treatment of this contaminated groundwater during closure or over the long term.[27] The FEIS clearly required that Category 1 containment system contact water be treated during reclamation (years 21-30 and years 31-52) as well as during a period of post-closure "long-term mechanical treatment."[28]

A supplemental EIS is needed to provide missing information and evaluate environmental issues, including but not limited to providing information and analysis regarding: 1) impacts on the Partridge River resulting from the shorter distance for seepage of highly polluted wastewater from equalization basins; 2) increased risk of mine site construction contact wastewater overflow; 3) increased risk of pipeline rupture and contamination of wetlands with concentrated pollutants; 4) potential increases in water volumes at the Tailings Basin; 5) potential increases in chemical contamination at the Tailings Basin, West Pit and East Pit; and 6) reduced capacity to respond to higher-than-predicted groundwater and surface water contamination or secondary wetlands impacts during operations, reclamation and long-term closure through adaptive management of water quality and quantity at the mine site.

A supplemental EIS is also needed to take a hard look at whether PolyMet's current project plan submitted in its most recent water appropriations permits alters the fundamental requirement in the FEIS that containment system water from the Category 1 waste rock pile be treated and retained in the mine site watershed during reclamation and long-term closure after mining operations cease.

3. New Information Regarding Water Appropriation from Mine Site

Neither the August 2013 PolyMet Section 404 Application nor the November 2015 PolyMet NorthMet FEIS disclosed the total volume of water that would be appropriated from the mine site to the plant site watershed nine miles away. Neither the PolyMet NorthMet SDEIS nor the FEIS disclosed the nature and extent of appropriations from mine site infrastructure or provided a water balance for all NorthMet Project facilities.[29]

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[25] *Id.*, pp. 1, 8.
[26] *Id.*, p. 3.
[27] *Id*, Table 3-1 and Table 5-1 (Attachment J). PolyMet's most recent Water Approp. Permit App. illustrates water appropriations during construction and operations (Large Figures 2, 3 and 4 on autop. 187-189), but provides no illustrations for reclamation and closure timeframes.
[28] FEIS, Figures 3.2-17, 3.2-18, 3.2-19 (Attachment K).
[29] Although this deficiency was pointed out in expert comments on the PolyMet NorthMet SDEIS, Lee (2014), pp. 5, 9, (Attachment L), it was not rectified in the FEIS.

To the extent that the FEIS discussed capture and retention of contact water at the mine site, the FEIS represented that "During mine operations and reclamation, surface water runoff from much of the Mine Site would be retained within the site until the West Pit floods."[30] The FEIS asserted that average annual flows in the Partridge River just downstream of the mine site would be reduced no more than 4% and mine site tributaries would remain within the range of natural variation.[31] The FEIS explicitly claimed that by approximately year 50, once the West Pit was filled, groundwater levels would be returned to near pre-mining conditions.[32]

No analysis of PolyMet NorthMet mine wetlands drawdown was calculated using a hydrologic model that considered the impacts of all water appropriations from the mine site watershed. More specifically, actual water appropriations from the mine site were neither quantified nor considered in evaluating mine site wetlands drawdown and impairment, since the only predictions made by PolyMet and adopted in the FEIS were based on an "analog" from another mine pit.[33]

According to PolyMet's most recent Water Appropriation Permit Applications for the project, the maximum annual volume of water pumped from the Partridge River headwaters and transferred to the PolyMet NorthMet plant site nine miles away would total 3,700,000,000 gallons (3,700 MG).[34] In addition to the East Pit (1,000 MG), the Central Pit (700 MG) and the West Pit (800 MG), each of which, according to the FEIS would be dewatered between mine years 0 through 20,[35] the most recent PolyMet Water Appropriations Permit Applications propose appropriations of 1,200,000,000 gallons per year (1,200 MG) due to mine site infrastructure.[36]

PolyMet's updated Water Appropriation Permit Application Permitting and Reporting System forms detail the nature of mine site infrastructure water usage.[37] The maximum water appropriation for the Category 1 stockpile groundwater containment system pumping alone is 14,400 gallons per minute.[38] This is equivalent to 756,864,000 gallons per year (757 MG), which is comparable in scale to the dewatering appropriation for either the Central Pit or the West Pit at the proposed NorthMet mine. Unlike mine pit dewatering, which is described in the FEIS as finite in duration, collection and pumping from the Category 1 stockpile groundwater containment system was described in the FEIS to continue indefinitely and for the foreseeable long-term future.[39]

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[30] FEIS, 5-132.
[31] *Id*., 5-453 maximum of 4% reduction at SW-004a and reduction in mine site tributary streams to Partridge by no more than 20%, thus within "the range of natural variability."
[32] *Id*., 5-110, "During years 20 to 52, water from the Plant Site would be pumped to the West Pit to accelerate flooding and help return groundwater levels to near pre-mining conditions."
[33] *Id*., *see e.g*. 5-112 to 5-113.
[34] Water Approp. Permits App., Table 5-3 and Table 6-1 (Attachment M). See also *Id*., MDNR Permitting and Reporting System forms, autop. 1-107.
[35] FEIS, *see e.g*. 5-110. See also Water Approp. Permits App., Table 3-1 and Table 5-1 (Attachment J).
[36] Water Approp. Permits App., Table 5-3 (Attachment M).
[37] Water Approp. Permits App., MDNR Permitting and Reporting System forms, autop. 44-59.
[38] *Id*., autop. 52, 141
[39] FEIS, 3-81, 3-141, 5-8.

None of the FEIS analyses of impacts to the Partridge River or its mine site tributaries reflect the new information on the volume and points of discharge for total water appropriations contained in the updated PolyMet NorthMet water appropriations permit applications.[40]

In addition, none of the "analog" mine pits used by PolyMet or regulatory agencies in place of water modeling to estimate secondary wetlands impacts for the PolyMet NorthMet mine included the feature of substantial and potentially indefinite long-term mine site water appropriations for containment and pumping of contaminated water nine miles away from the mine site. This important discrepancy requires a supplemental EIS analysis of secondary wetlands impacts, which analysis must be based on modeling of all water appropriations for mine site infrastructure as well as modeling of mine pit dewatering, based on appropriate testing and calibration.

Conclusion
The request by WaterLegacy, among other stakeholders, during the PolyMet NorthMet FEIS comment period for a hearing should be granted pursuant to the Clean Water Act, 33 U.S.C. §1344(a) and Part 327 of Title 33 of the Code of Federal Regulations. The request was properly and timely made, the issues raised are substantial and there are valid interests to be served by a hearing.

In addition, based on information brought to light in the Minnesota state permitting process of significant new circumstances and information relevant to environmental concerns and bearing on the proposed PolyMet NorthMet action and its impacts, a supplemental EIS is necessary under NEPA and its implementing federal regulations. 42 U.S.C. §4332(2)(C); 40 C.F.R. §1502.9(c)(1)(ii); 33 C.F.R. § 230.13(b).

We look forward to your prompt response on these important issues. Thank you for your consideration.

Sincerely yours,

Paula G. Maccabee

Paula Goodman Maccabee
Advocacy Director/Counsel for WaterLegacy

Attachments

cc: U.S.D.A. Forest Service
Minnesota Department of Natural Resources
U.S. EPA Region 5
Fond du Lac Band of Lake Superior Chippewa
Grand Portage Band of Lake Superior Chippewa
Bois Forte Band of Lake Superior Chippewa

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[40] *See* footnote 31, *supra*.

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LIQUEFACTION SUSCEPTIBILITY OF SILTY SOILS

[1]DILPREET SINGH, [2]ARSHDEEP SINGH, [3]GURWINDER SINGH, [4]ARSHVEER SINGH, [5]JASPREET SINGH

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Abstract— The phenomenon of liquefaction which has done considerable loss over the years is often associated with sandy soils whereas same level of emphasis is not given to silt. To determine the extent of remedial measures required for a soil against liquefaction, susceptibility to liquefaction of the same must be checked. This paper advocates a simple criterion based on two key soil parameters that differentiate liquefiable and non-liquefiable silts. Firstly, some imperative physical characteristics of silts are briefly discussed to clarify the misconceptions about silts. Following that, clay content and liquid limit are taken as two key parameters that help partition liquefiable and non-liquefiable silts. Analogy between liquid limit and the shear strength of silts is used to show that liquid limit can be regarded as a key soil parameter to measure liquefaction susceptibility. Need of using clay content as another factor is also discussed, while explaining the inadequacies of basing criterion for liquefaction of silts on just one key parameter. The applicability of using clay content as a key soil parameter is also illustrated using several case histories. Lastly, this research paper leads to the promotion off simple criteria for liquefaction of silts, utilizing together both the clay content and the liquid limit soil parameters.

Index Terms— Susceptibility, liquefaction, liquid limit, strength.

I. INTRODUCTION

Recent experience with earth failure in low plasticity silts and clay's, during vibrant earthquakes, have pointed up the fact that seismic forces can spark the development of substantial strain and strength loss over a wide range of saturated soil from clay's to sand.
However, the earthquakes which induced ground failure are less frequent in silts, but a number of cases have expressed the need for a better understanding of seismic behavior of fine grained soils and for an engineering procedure that are most suitable for differential liquefiable and non-liquefiable and non-liquefiable silts.
There is insufficient guidance on engineering procedure that is most suitable for evaluating potential strains and strength loss, particularly for silts. Hence, it is common to compare the results of current susceptibility criteria that exist, which were developed for sands.
This paper present liquefaction susceptibility criteria based on two 'Key' soil parameters, clay content and liquid limit.

II. SUSCEPTIBILITY OF SILTS TO LIQUEFACTION

There is a lot of confusion in geotechnical engineering about liquefaction susceptibility of silty soils. It is noticed that liquefaction susceptibility of silts must fall somewhere between high susceptibility of sand and the non-susceptibility of clays, as the grain size of silt particles lies in between the sand and clay. In addition to it, liquefaction susceptibility of silt is further exasperated where silts and clay are categorized under one leading finest.
Silt, indeed are very fine sand and have grain size less than 0.074m. Silt grains cannot be seen by naked eyes, but this fact does not significantly veer physical characteristics of silt grains to that of sand grain.
For example, silt grains and sand grains are generally of same shape and comprise of rock forming mineral. Alike, sand grains, attraction force such as hydrogen bond and van-der waals bond are negligible between silt grains.
The soil of grain finer than 0.02mm is regarded as clay and they bear very less similarity to sand and silts. Since, clay particles are comprised of clay minerals; they have high plasticity and tend to be platey shape. Moreover, hydrogen and van-der waals forces of attraction exist between the particles due to which clays exhibit plastic nature. Based on the comparison of silts and clay, silts are more similar to sand.
Now, the doubt arises, at what clay content susceptibility of silt changes from liquefaction susceptibility of sands to that of clay?

III. KEY SOIL PARAMETERS THAT DIFFERENTIATE LIQUEFIABLE AND NON-LIQUEFIABLE SILTS

The clayey soil prone to potential strain and severe strength loss, as outlined by Seed etal. (1983), from case history of china's earthquake, by which Wang (1979) expected to have following characteristics;

Clay Content	<15%
Liquid Limit	>35%
And Water Content	>0.9(L.L)

To fortify the criteria outlined by seed et al. and promote their application to silts, further case

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histories are used in this paper. However, it is worth noting that water content is not considered as key Parameter, as its value changes remarkably according to environmental conditions.

IV. CLAY CONTENT

A plethora of case histories evidence that silt having low clay content is highly sensitive to liquefaction. A brief discussion of case histories is as under:

Kishida (1970) inspected the grain size distribution of soils generated at Nanechama Beach, Japan during Tokachioki earthquake of 1968. The figure indicates that the soil which liquefied was very silty and had clay content less than 10%.

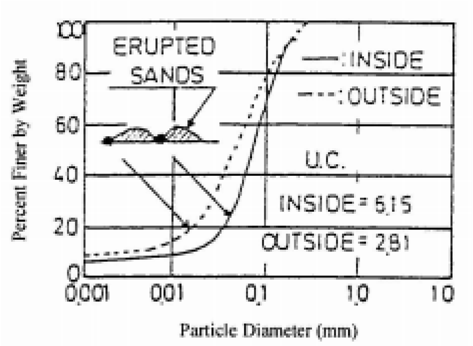

Figure 1: Soil Boils (GRAIN DISTRIBUTION CURVE)

Kishida points out that grain size distribution of boils showed resemblance with grain size distribution of soil located at a depth 1m to 12m. However, the grain size distribution of the boils did not match those soils at depth 12m to 17m. These soils had clay content more than 10% and did not liquefy.

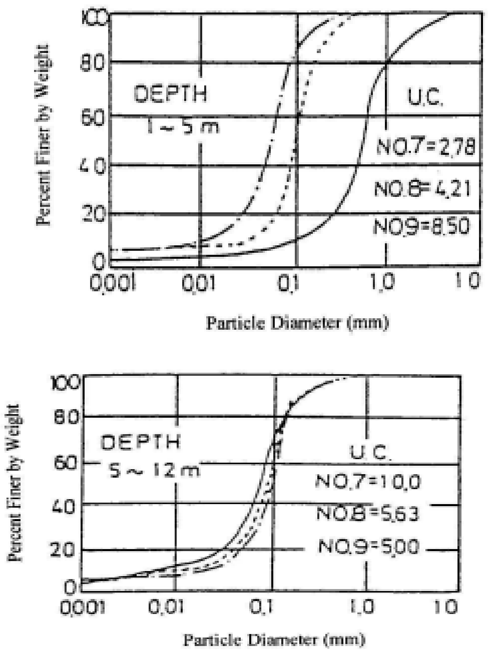

Figure 2: Grain Size Distribution of Soils

Figueroa et al. (1995) determine this grain size distribution of soil samples called from sand boils formed at the lower San Fernando Dam, California during north bridge earthquake of 1994. The curve is shown in Fig. 1. The soil formed to be very silt with clay content less than 10%.

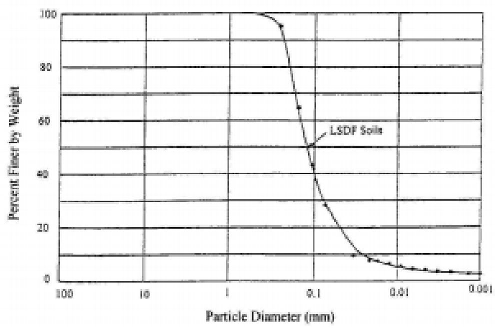

Figure 3: LSFD Soils

Tokimatsu and Yoshimi (1983), after an intensive research collected, 90 case histories of liquefaction (70 inside Japan from 10 earthquake and 20 outside Japan). They proposed a triangular classification chart representing the grain sizes of silty sand to slightly sand silt soils.

By defining clay as grains finer than 0.005mm, they depicts a cut off for liquefaction susceptibility at clay content 20%, however, a cut off at clay content may be more accurate. On the other hand, if clay is defined as grains finer than 0.002mm, a final cut off at clay content of about 10% would be appropriate.

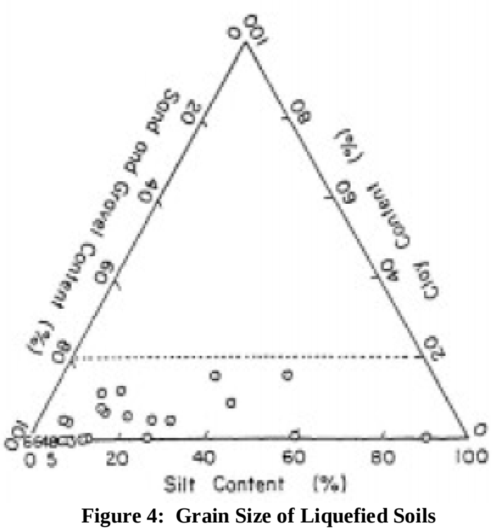

Figure 4: Grain Size of Liquefied Soils

Tuttle et. al (1990) published liquefaction failures occurred during saguenay earthquake of 1998 at Ferland, Canada. As indicated by grain size distribution curve of the sand boils erupted, the soil liquefying was a very silty sand to slightly silt having clay content less than 10%. Soil laid at depth 1.5m to 9m advocates strength loss. Clayey silts at depth of about 9m to 11m were not erupted in boils and seem to have not liquefied.

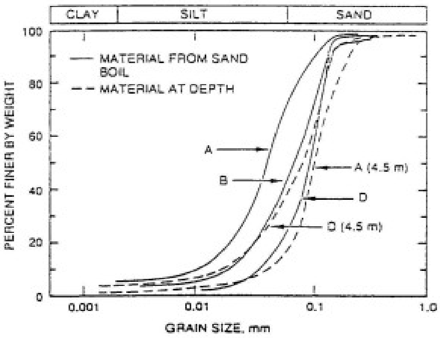

Figure 5: Grain Size Distribution of Soils

Zhou(1981) examined the liquefaction that arose in Tangshan, China during Tangshan earthquake of 1976. Lutai, southwest of Tangshan, was the most affected area. Across section of several soil layers are shown in Fig. 33333. Similar patterns of grain size distribution curve were also seen and clay content of the soil erupted in soil boils was found to be less than 10%.

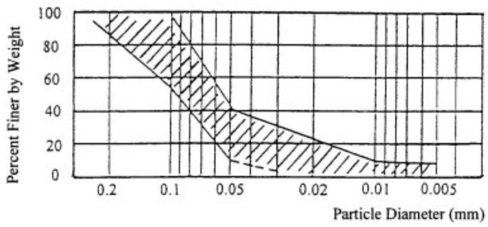

Figure 6: Ejecta Grain Size distribution Curve

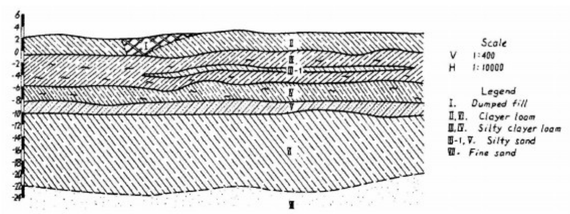

Figure7: Lutai Area stratigraphy

Zhou (1981) illustrated the grain size distribution of layer 3 and layer 2 of Lutai area. According to Zhou, layer 3 exist only in some parts of Lutai area, and consists of a less deposit 0.5 to 1.0 thick, located at a depth of 6m. For layer 5 soilswere found to be sandy to slightly sandy silt with clay content 19% (for clay finer than 0.005mm). For clay finer than 0.002mm, it could be supposed that the clay content is up to say 15%.

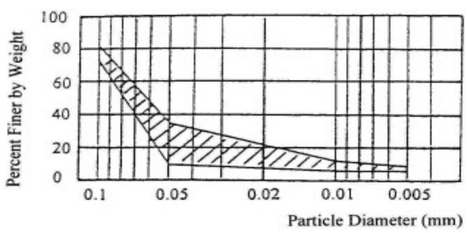

Figure 8: Layer III-1 Curve

According to Zhou, layer 5, which is presented all over the Lutai, about 2.5m thick and positioned at a depth of about 10m. Considerably, in a macro-survey it was found that in areas where both lenses layer 3 and 5 were present, severe eruption occurred. However, no significant eruption occurred where only high clay content layer 5 was present.

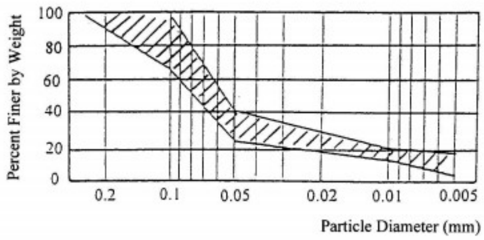

Figure 9: Layer V Distribution Curve

The aforementioned case histories illuminate liquefaction of silty soils and further relevancy of using
Clay content is a 'Key' soil parameter that differentiates liquefiable and non-liquefiable silts. In addition to this, the clay content is criterion highlighted by Seed at. el (1983) is strengthen by these case histories. The criteria developed is also reinforced by seed et al. (1964) where it was depicted that at about 10% natural clay content, Skelton voids in a sand would be filled with clay. Hence for clay contents greater than 10%, soil is termed as non-liquefiable.

V. LIQUID LIMIT

The liquid limit of a soil is defined as the water content at which the soil has a shear strength of approximately 25 gm/cm^2 seed et al (1964) or simply the minimum water content at which soil changes from liquid state to plastic state.
Seed et al (1983) also described liquid limit criterion among the three criteria for estimating potential strain and strength loss during severe earthquakes. Intergranular attraction forces reward shear strength to plastic soils. As the water content, void ratio and inter grain spacing are interconnected liquid limit can be visualized as a measure of grain spacing at which attraction forces provides a shear strength of 25 gm/cm^2. Consequently, a silty sand with high liquid limit will have a high net attractive force between any clay particles present and on the other hand, a silty soil with low liquid will possess less net attractive forces. Attractive forces tend to resist liquefaction, bestowing on silty soil a relatively low vulnerability to liquefaction. This fact defines the liquid limit as a key soil parameter that differentiate liquefiable and non-liquefiable silts.
Moreover, liquid limit is also proportional to clay content seed et al (1964) and maximum liquid limit of naturally occurring clays is 300. For a liquefiable soil,

an upper limit of about 30 consistent with 10% clay criterion explained above.

VI. REFINEMENT OF CRITERIA FOR LIQUEFACTION OF SILTY SOILS

A criterion solely based on clay content does not hold good for all the conditions, where at one extreme, clay sized grains are non-plastic and at other extreme, non-clay sized grains shows plastic nature. A fine illustration of first case is mining and quarry tailings. These tailings often have clay sized non-plastic crushed stone grains. On the other hand, Mica is the perfect example of latter case. Mica rock forming minerals are completely opposite to clay minerals, illite and montmorillonite. Mica have grains similar to silt possess plasticity. Using liquid limit along with clay content criteria can eradicate errors during these extremities.

Seed et al (1983) liquid limit criteria was based on Chinese PRC data which uses PRC fall cone penetration apparatus to find liquid limit. Koester compared the liquid limit results given by Casagrande's type percussion apparatus and PRC fall cone penetration apparatus and observed that PRC method gave a higher value of liquid limit. As per Koester, a liquid limit value of 35 determined by PRC fall cone penetration is equivalent to a liquid limit of about 32 determined by Casangrande's type percussion apparatus.

CONCLUSION

The following concluding statements can be made:

1. There is an ample data showing that silts are vulnerable to strength loss and potential strains.
2. Clay Content can be regarded as a 'Key' soil parameter that differentiate liquefiable and non-liquefiable silts.
3. Liquid limit can be regarded as a 'Key' soil parameter that differentiate liquefiable and non-liquefiable silts.
4. Use of liquid limit criteria along with clay content criterion helps explore cases where clay sized particles are non-plastic and non-clay sized particles are plastic.

Based on the case histories and theory presented above, a fortified version of Seed et al (1983) criteria is given in following table.

	Liquid Limit < 32	Liquid Limit > 32
Clay Content < 10%	Susceptible	Further Studies Required (Examining plastic non clay size grains such as Mica)
Clay Content > 10%	Further Studies Required (Examining non-plastic clay sized particles such as mining tailings)	Not Susceptible

Notes:
1)Liquid limit determined by Casagrande's apparatus.
2)Clay defined as grains finer than .002mm.

REFERENCES

[1] J. L. Figueroa, A. S. Saada, "effect of grain size on theenergy per unit volume at the onset of liquefaction,"*Proceedings: 3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,* Vol. 1, 1995.

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GALE-TEC ENGINEERING, INC.

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WAYZATA, MN 55391
TELEPHONE (952) 473-7193 FAX (952) 473-1492
www.gale-tec.com

September 26, 2017

Mr. Cecilio Oliver, P.E.
Emonds & Oliver Resources Inc.
7030 6th St. North
Oakdale, MN 55128-6146

Re: Proposal for Geotechnical Engineering Review of Polymet Hydromet. Residue Facility Foundation Design

Dear Mr. Oliver:

In accordance with your request, we are pleased to provide you with this proposal for services on the above referenced project.

We understand that the MPCA and MnDNR are currently reviewing the Polymet Dam Safety Permit and Permit to Mine and have expressed concerns about the design of the Hydromet. Residue Facility, which has been proposed to be constructed within a low area the previously served as the LTVSMC Emergency Discharge Basin. The permitting agencies are concerned about potential different settlement caused by the basin construction and potential distress to the double composite liner system that has been proposed to unlay the facility and minimize the potential for environmental contamination.

We have developed the attached spreadsheet that contains our proposed scope of work and fee schedule after consulting with the MPCA and EOR. We look forward to the opportunity to work with you and the MPCA and MnDNR in the Permitting Process.

Respectfully,

GALE-TEC ENGINEERING, INC.

Stephan M. Gale, P.E.
Principal Engineer

Nathan M. Lichty, P.E.
Project Engineer

Enclosures: Spreadsheet Detailing Scope of Work and Proposed Fee
NML
PROPOSAL/EOR, Polymet HRF Foundation Design

MPCA/MDNR - Evaluation of PolyMet HydroMet. Residual Facility Foundation Design

Labor

	Project Manager - Cecilio Olivier, P.E.	Project Engineer - Nate Lichty, P.E.	Principal Engineer - Steve Gale, P.E.	Principal Engineer - Dr. Barry Christopher	Clerical - Paula Kelly	Total	Task Total
Task 1 - Overall Project Administration/Project Set-up and Contract Management	15		15		2	32	$ 7,113.00
Task 2 - Review Subsurface Conditions from Polymet Geotechnical Report		8	2	2		12	$ 2,530.00
Task 3 - Evaluate Existing Preload Design		8	5	2		15	$ 3,220.00
Task 4 - Analyze and Develop Soil Conditions and Settlement Characterists of HRF Foundation Soils		20	5	2		27	$ 5,290.00
Task 5 - Perform Settlement Analysis using Conventional Consolidation Setttlement Theory along 4 Cross Sections (Two Oriented North-South and Two Oriented East-West)		20	8	5		33	$ 7,015.00
Task 6- Perform Settlement Analysis using Finite Element Computer Program SIGMA-W		20	8	5		33	$ 7,015.00
Task 7 - Use Results of Both Settlement Analyses to Estimate Differential Settlement along proposed Liner System		20	8	5		33	$ 7,015.00
Task 8 - Evaluate Three (3) Thicknesses of Preload Design with and without Wick Drains as a Settlement Mitigation Technique		40	20	10		70	$ 14,950.00
Task 9 - Prepare and Review Geotechnical Report for MPCA/MnDNR Review	8	20	30	5	10	73	$ 14,645.00
Task 10 - Two Meetings with MPCA/MDNR	4	5	5			14	$ 2,952.50
Task 11 - Finalize and Review Geotechnical Report on HRF Foundation Design	4	5	5		4	18	$ 3,228.50
Total Hours	*31*	*166*	*111*	*36*	*16*	*360*	
Hourly Rate	$ 235.00	$ 172.50	$ 230.00	$ 345.00	$ 69.00		
Subtotal Labor	***$ 7,285.00***	***$ 28,635.00***	***$ 25,530.00***	***$ 12,420.00***	***$ 1,104.00***	***$ 74,974.00***	

Expenses

Task		Total
1. Mileage - Meetings (140 miles @ $.535/mile) =		$ 86.13
Subtotal Expenses		**$ 86.13**
TOTAL FEE & EXPENSES		**$ 75,060.13**

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File

STATE OF MINNESOTA
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF WATERS

P.A. No. 81-2100

444 Lafayette Road, Space Center Building, St. Paul, Minnesota 55101

IN THE MATTER OF THE APPLICATION OF ERIE MINING CO. A LIMITED PARTNERSHIP AND MANAGED BY PICKANDS MATHER & CO.

for a PERMIT TO construct and operate a Taconite Tailings Disposal Dam

St. Louis County.

PERMIT

Pursuant to Minnesota Statutes, Chapter 105, and on the basis of statements and information contained in the permit application, letters, maps, and plans submitted by the applicant, and other supporting data, all of which are made a part hereof by reference, PERMISSION IS HEREBY GRANTED to Erie Mining Co., A Limited Partnership whose address for the purpose of notices and other communications pertaining to this permit is P.O. Box 847, Hoyt Lks, MN 55750 which address is subject to change by written notice from the permittee.

To construct and operate an existing taconite tailings disposal dam and to construct a NE increment of the existing basin known as the "North East Extension" in connection with the operation of the Erie Mining Company's Taconite production plant north of Hoyt Lakes, MN. The project is described in the documents, information, maps and plans submitted by the permittee or by the permittee's designer or agent on the permittee's behalf including: Application for Permit titled "Erie Mining Company. Application for Tailing Basin Permit. June 1981", Engineering Report and Supplement No. 1 produced by EBASCO Services Inc. and signed on 6/3/81 titled "Erie Mining Company, Hoyt Lakes,MN. Tailing Disposal Basin, Tailing Dam Investigation and Analyses."

PROPERTY DESCRIBED on Exhibit I (attached) and made a part of this permit.

for the purpose of Disposal of Taconite Tailings St. Louis COUNTY

This permit is granted subject to the following GENERAL and SPECIAL PROVISIONS:

GENERAL PROVISIONS

1. This permit is permissive only and shall not release the permittee from any liability or obligation imposed by Minnesota Statutes, Federal Law or local ordinances relating thereto and shall remain in force subject to all conditions and limitations now or hereafter imposed by law.
2. This permit is not assignable except with the written consent of the Commissioner of Natural Resources.
3. ~~XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX~~
4. No change shall be made, without written permission previously obtained from the Commissioner of Natural Resources, in the hydraulic dimensions, capacity or location of any items of work authorized hereunder.
5. The permittee shall grant access to the site at all reasonable times during and after construction to authorized representatives of the Commissioner of Natural Resources for inspection of the work authorized hereunder.
6. This Permit may be terminated by the Commissioner of Natural Resources, without notice, at any time he deems it necessary for the conservation of the water resources of the state, or in the interest of public health and welfare, or for violation of any of the provisions of this permit, unless otherwise provided in the Special Provisions.

SPECIAL PROVISIONS

I. Construction work authorized under this permit shall be completed on or before June 30, 1986. Upon written request to the Commissioner by the Permittee, stating the reason therefore, an extention of time may be obtained.

II. The excavation of soil authorized herein shall not be construed to include the removal of organic matter DOES NOT APPLY unless the area from which such organic matter is removed is impervious or is sealed by the application of bentonite after excavation.

III. In all cases where the doing by the permittee of anything authorized by this permit shall involve the taking, using, or damaging of any property rights or interests of any other person or persons, or of any publicly owned lands or improvements thereon or interests therein, the permittee, before proceeding therewith, shall obtain the written consent of all persons, agencies, or authorities concerned, and shall acquire all property, rights and interests necessary therefor.

IV. This permit is permissive only. No liability shall be imposed upon or incurred by the State of Minnesota or any of its officers, agents or employees, officially or personally, on account of the granting hereof or on account of any damage to any person or property resulting from any act or omission of the permittee or any of its agents, employees, or contractors relating to any matter hereunder. This permit shall not be construed as estopping or limiting any legal claims or right of action of any person other than the state against the permittee, its agents, employees, or contractors, for any damage or injury resulting from any such act or omission, or as estopping or limiting any legal claim or right of action of the state against the permittee, its agents, employees, or contractors for violation of or failure to comply with the provisions of the permit or applicable provisions of law.

V. No material excavated by authority of this permit nor material from any other source, except as specified herein, shall be placed on any portion of the bed of said waters which lies below DOES NOT APPLY. It shall be the duty of the permittee to determine correctly all pertinent elevations at the site of the work for the purpose of complying with the conditions of this permit.

VI. Any extension of the surface of said waters resulting from work authorized by this permit shall become public waters and left open and unobstructed for use by the public. (SEE ATTACHED SHEETS FOR ADDITIONAL SPECIAL PROVISIONS)

(over)

ADDITIONAL SPECIAL PROVISIONS

VII. PERIOD OF AUTHORIZATION

The authorized construction is limited to that detailed in references listed above and is further limited to that work proposed for the first 5 years of the design. Periodic 5 year extensions shall be granted by the Commissioner upon written request by the owner provided that past construction has been shown to be adequate and in compliance with approved plans and that future plans are in compliance with current prudent engineering practices at the time of the request for extension.

VIII. COMPLIANCE WITH OTHER LAWS

The authorized activities herein shall be subject to all Federal, State and local laws, rules, and regulations in effect now or adopted hereafter relating to such structures, facilities, and operations authorized herein.

Although it is the intent of the Commissioner to maintain consistency with the permits or approvals of other agencies, nothing in this approval shall waive or abrogate any other state or federal approvals or permits which may be necessary for the Permittee's dams and tailings basin. The terms and conditions, whether similar or more stringent, which may appear in any other permit or approval.

IX. MINELAND RECLAMATION

The Permittee shall comply with all mineland reclamation proceedures as detailed in "Rules Relating to Mineland Reclamation 6 MCAR 1.0401-1.0407". Prior to renewal of this permit the Permittee shall submit to the Commissioner for his approval a plan for reclamation of the dam and tailings basin.

X. MONITORING AND MITIGATION OF AIR, SURFACE AND GROUND WATER POLLUTION

The Permittee shall comply with all standards and regulations of the MPCA relating to air, surface and ground water pollution..

XI. LIABILITY OF PERMITTEE

The Permittee shall assume all legal risks and liabilities, including without limitation those for damages or any injury to persons or property, arising from the construction, operation, maintenance or closure of these tailings dams, basin, and other activities authorized under this approval.

XII. RESPONSIBILITY FOR CONTROL

The Permittee, in cooperation with its designer, shall be responsible for providing adequate controls on construction and operation activities, and for verifying design, construction and operation assumptions.

ADDITIONAL SPECIAL PROVISIONS

XIII. CONFORMITY WITH APPROVED DESIGNS, PLANS AND SPECIFICATIONS AND REVOCATION OF PERMIT

If at any time during construction of a project, the Commissioner finds that the work is not being done in conformance with approved designs, plans and specifications, the Commissioner shall notify the Permittee and shall order immediate compliance and may order that no further work be done until such compliance has been effected and approved.

If the Permittee fails to comply with the terms of this permit of with approved designs, plans and specifications or if conditions are revealed which will not permit the construction of a safe dam, the permit may be revoked.

XIV. EMERGENCY WORK

If the Permittee finds at any time during construction or operation that, in order to adequately protect the environment or public health, safety or welfare, immediate alterations to the approved plans and specifications are required, the alterations may be started, but the Permittee shall promtly notify the Commissioner of such requirements. If the alterations are to remain as permanent project features, the Permittee shall, as soon as practicable, revise the plans and specifications and submit the revisions, in writing, to the Commissioner for approval.

XV. UNFORESEEN CONDITIONS

The Permittee shall immediately notify the Commissioner of any conditions relating to structural suitability or water impacts discovered during construction or operations which differ from those identified in the approved plans and specifications. If such conditions require modification of the approved plans and specifications, the Permittee shall prepare such modification and submit them to the Commissioner for his approval.

XVI. PERMANENT MARKERS

A minimum of two (2) permanent markers for vertical and horizontal control shall be established in the natural ground by the Permittee in the vicinity of the dam. The permanent markers for vertical control must be based upon sea level datum. The accuracy of these markers shall be certified by the designer (or his representative), or a registered professional land surveyor. Each marker shall be located so as to be accessible and protected against disturbance throughout the projected life of the tailing basin. The Permittee shall within 90 days of the issuance of this approval submit to the Commissioner the locations of these permanent markers, plotted on standard U.S. Geological Survey topographic maps or other more detailed contour maps.

ADDITIONAL SPECIAL PROVISIONS

XVII. TEMPORARY REDUCTION OR CESSATION OF OPERATIONS

The Permittee shall immediately notify the Commisioner in the event of any plant or disposal system malfunction or operational change which requires a temporary reduction or modification or cessation of plant or waste disposal system operations. In no case shall the Permittee discharge wastes or process water to areas other than those within the tailings basin.

XVIII. TRANSFER OF OWNERSHIP

The owner(s) shall not transfer the ownership of the dam without a written permit from the Commissioner.

XIX. CLOSED SYSTEM

The entire tailings basin shall be a closed-circuit operation, i.e. all surface and seepage waters shall be collected and returned to the basin; or be treated and released to the environment pursuant to MPCA's permitting authority. The excess runoff and transport water ponded over the settled wastes shall be reclaimed for reuse in the plant operations.

XX. RATE OF INCREASE IN HEIGHT

The increase in dam height shall be limited to no more than 15 feet per year; greater yearly increases shall require written approval by the Commissioner.

XXI. ESTABLISHMENT OF SURFACE PROTECTION

The Permittee shall, as soon as practicable following the construction of a portion of the dam cover, protect or establish vegetative cover on the dam surfaces for the prevention of soil erosion.

The Permittee shall keep the surface of the tailings disposed of within the basin, inundated, moist, or covered with appropriate chemicals or vegetation in order to minimize potential fugitive dust problems.

XXII. FREEBOARD AT DAM

During normal operational conditions, the water level upstream of the dam shall not be allowed to rise above an elevation 11 feet below the top of the dam. The water surface in the basin shall not be permitted closer than 200 feet to the dam crest (measured horizontally).

XXIII. LOCATION OF TAILINGS TRANSPORT PIPELINES

Tailings transport pipelines shall be located away from the outside crest of the dam such that any breakage or misoperation of them will not result in tailings being spilled onto the downstream surface of the dam.

ADDITIONAL SPECIAL PROVISIONS

XXIV. SAFETY BERMS ON DAM LIFTS

Any safety berms located on the horizontal lift portions of the dam shall be constructed in such a manner that they will not impound water.

XXV. INSPECTION, MONITORING AND REPORTING OF CONSTRUCTION

The Permittee shall submit a yearly report to the Commissioner covering the past year's construction and proposed construction for the coming year. The report shall be submitted by January 31 of each year. The frequency of the report may be changed if deemed neccesary by the Commissioner.

The report shall include, but not limited to routine construction documentation; construction quality control tests; summaries of actual tests of foundation and embankment materials, instrumentation installation and maintenance of instrumentation records; preparation of logs of drill holes and other exploration features, if any, completed during construction; reveiw and evaluation of disclosed field conditions by the designer; logs of incidents involving the dam where routine or emergency maintenance work was required and logs of time spent on such activities; construction problems encountered, records or the amounts of materials entering and leaving the disposal basin, records of the amounts of any discharges of treated water released to the environment; aerial photos and updated maps of the basin and any other items which may be pertinent to a construction quality assurance program.

The Permittee shall also submit yearly a performance report to the Commissioner detailing the instrumentation data and engineering analysis and interpretation of these data as they relate to the safety of the structures and the design assumptions.

The construction reports should be prepared by a registered professional engineer and shall certify that construction was in accordance with approved plans and specifications or approved revisions therof.

A detailed engineering report shall be submitted to the Commissioner after every 50 foot rise in vertical elevation of the dam. The report shall address stability and adequacy of the dam.

XXVI. MAINTENANCE

The project components authorized herein shall be properly maintained in order to achieve their intended and authorized functions, and in compliance with the terms and conditions of this approval.

The Permittee shall perpetually maintain the tailings basin and all its parts so as to insure the integrity of all structures and to prevent the deposited wastes from entering the waters of the state.

The Commissioner may impose such requirements as may be necessary, prior to the ultimate termination of the Permittee's operations, to insure that the Permittee will remain financially responsible for carrying out the activities required for perpetual maintenance, and that adequate funding will exist therefor.

ADDITIONAL SPECIAL PROVISIONS

(CONT) Logs of time spent on maintenance activities shall be developed and submitted to the Commissioner with the yearly construction reports.

XXVII. INSPECTION FEES

Initial and periodic inspection fees shall be required as per the Dam Safety Rules 6 MCAR 1.5034 K.. The Permittee shall submit to the Commissioner with the yearly construction report a detailed accounting of the cost of construction for the past year and an estimate of the construction cost for the future year. The amount of the fee should be estimated by the Permittee and submitted in the form of a check payable to the State Treasurer along with the yearly construction report.

XXVIII. RECORDS OF INCIDENTS

Logs shall be kept of all "incidents" involving the dam which affected normal construction or operating procedures such as pipeline breaks, development of erosion or slide areas, etc.. The logs shall include description of the incidents and actions taken regarding them. The logs shall be submitted to the Commissioner with the yearly construction reports.

XXIX. SUCCESSORS

The terms and provisions of this permit shall extend to and bind the successors in authority of the Commissioner and the legally assigned successors in interest of the Permittee.

XXX. ACCEPTANCE OF PERMIT

Undertaking or initiating any work or part thereof authorized herein by the Permittee constitutes acceptance of the permit and all its terms and conditions.

XXXI. DEED REGISTRATION, NOTICE OF PERMIT CARD, AND EFFECTIVE DATE

This permit shall be recorded in the office of the Register of Deeds of St. Louis County, and a date stamped copy thereof furnished to the Division of Waters, Department of Natural Resources, 444 Lafayette Road, St. Paul, Minnesota 55101.

cc: James F. Cooper
: Paul Pjar, Div. of Minerals
: Robert Criswell, PCA
: Region 2 Hydrologist
: St. Louis Co. Zoning
: North St. Louis SWCD
: St. Louis WSD
: USCE
✓: P.A. 81-2100 file

Executed at St. Paul, Minnesota

this 20 day of July, 1981

COMMISSIONER OF NATURAL RESOURCES

BY [signature]
Larry Seymour, Director
Division of Waters

STATE OF MINNESOTA)
) ss.
COUNTY OF)

On this 20 day of July, 1981, before me, a Notary Public within and for said County, personally appeared Larry Seymour, Director Division of Waters
(Name & Title)
to me personally known to be the person who executed the foregoing instrument on behalf of the State of Minnesota and acknowledged that he executed the same in his official capacity at his free act and deed, pursuant to the statutes in such case made and provided.

Jeanne M. Matczynski
Dakota County
My commission expires Dec. 30, 1986

[signature]
Notary Public, Dakota County, Minnesota
My commission expires Dec 30, 1986

Subject: RE: PolyMet Tailings Dam Comments Appendix 6
Date: Thursday, June 1, 2017 at 1:34:06 PM Central Daylight Time
From: Dostert, Dana M (DNR) (sent by FYDIBOHF23SPDLT </O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP /CN=RECIPIENTS/CN=71379F1408B04EC99DC113DEE43593AD-DANA DOSTER>)
To: Cecilio Olivier, donsutton@spectrum-eng.com, Boyle, Jason (DNR)
CC: Kunz, Michael (DNR), Stu Grubb

Slope stability models were run on the perimeter embankments using a variety of scenarios. Those scenarios included both drained and undrained embankment conditions. In addition, slope stability models were computed with water levels within the basin at levels expected from the 24-Hour Probable Maximum Flood. These models were run at numerous lifts all the way to closure. The specific information can be found in the geotechnical data package.

The geomorphological issues are essentially why I favor dry closure. I would like to be able to see Polymet be able to walk away from a site that no longer has seepage issues and can be allowed to revert to forest. Wet closure will not allow that.

Dana D.

Dana Dostert PE, PG
Senior Engineer – Dam Safety
MN Department of Natural Resources
500 Lafayette Road, St. Paul, MN 55155-4032
(651)-259-5663

mailto:dana.dostert@state.mn.us

From: Cecilio Olivier [mailto:colivier@eorinc.com]
Sent: Thursday, June 01, 2017 12:01 PM
To: Dostert, Dana M (DNR) <dana.dostert@state.mn.us>; donsutton@spectrum-eng.com; Boyle, Jason (DNR) <jason.boyle@state.mn.us>
Cc: Kunz, Michael (DNR) <michael.kunz@state.mn.us>; Stu Grubb <sgrubb@eorinc.com>
Subject: RE: PolyMet Tailings Dam Comments Appendix 6
Importance: High

Following Don's and Dana's comments below, it seems to me that there a couple of issues we need to address:

1. The tailings dam could be geotechnically stable but geomorphologically unstable. **Dana, Jason** – do you know if the geotechnical stability analysis was performed under spillway overflow AND saturated embankment? If not, do you recall the rational for not doing it this way?
2. All the points raised by Don regarding geomorphological issues are important and, short of a dry closure, they will require significant perpetual maintenance. Right now, the cost tha PolyMet is assuming for this maintenance tasks appears to be about $100K (this needs verification but seems very low to me). I know it is difficult, but we really need to estimate these annual costs for long term FA calculation purposes. **Don**, could you do that?

   My opinion is that, at a minimum, we need to include:
   - Annual maintenance costs for regular erosion patching, tree/vegetation replacement, regrading, etc.
   - Annualized cost of perpetual operation, maintenance, and capital replacement of the pumping system to maintain appropriate tailings water levels (pumping in or pumping out)
   - Annualized cost of major capital improvements like bentonite re-application (say every 10-20 years), structural issues, etc.
   - Annual monitoring and 3rd party dam safety consultant

It is not going to be cheap….. we need to know sooner than later.

Thanks,

Cecilio Olivier, PE
EOR: water | ecology | community
d: 651.203.6001 o: 651.770.8448

EOR - CELEBRATING 20 YEARS!

From: Dostert, Dana M (DNR) [mailto:dana.dostert@state.mn.us]
Sent: Thursday, June 1, 2017 8:17 AM
To: donsutton@spectrum-eng.com; Cecilio Olivier; 'Steve Gale'; Kunz, Michael (DNR); 'Nate Lichty'; Stu Grubb
Cc: Boyle, Jason (DNR)
Subject: RE: PolyMet Tailings Dam Comments Appendix 6

Hi Everybody,

Just as an update, I talked to Tom Radue earlier this week about the under drain. In the most recent plans revised about two weeks ago, they have renamed the two underdrain layers as foundation layers. Their primary purpose will be to provide foundation support for the perimeter dam and they will be constructed of gravel and coarse tailings. They were also meant to collect seepage waters and draw them back into the stack. The drainage area for these seepage collection sites is quite small, being the outside face of the dam, so there is unlikely to be a large volume of precipitation entering the stack. There groundwater model has not shown any issues with rising groundwater levels at this time.

We have not yet received the redesigned plans. More discussion will be needed.

Thanks,,

Dana D.

Dana Dostert PE, PG
Senior Engineer – Dam Safety
MN Department of Natural Resources
500 Lafayette Road, St. Paul, MN 55155-4032
(651)-259-5663

mailto:dana.dostert@state.mn.us

From: donsutton@spectrum-eng.com [mailto:donsutton@spectrum-eng.com]
Sent: Wednesday, May 31, 2017 5:18 PM
To: 'Cecilio Olivier' <colivier@eorinc.com>; 'Steve Gale' <smg@gale-tec.com>; Kunz, Michael (DNR) <michael.kunz@state.mn.us>; 'Nate Lichty' <nml@gale-tec.com>; 'Stu Grubb' <sgrubb@eorinc.com>
Cc: Boyle, Jason (DNR) <jason.boyle@state.mn.us>; Dostert, Dana M (DNR) <dana.dostert@state.mn.us>
Subject: PolyMet Tailings Dam Comments Appendix 6

Steve Gale, Nat Lichty and I discussed the FTB drawings in Appendix 6 today.

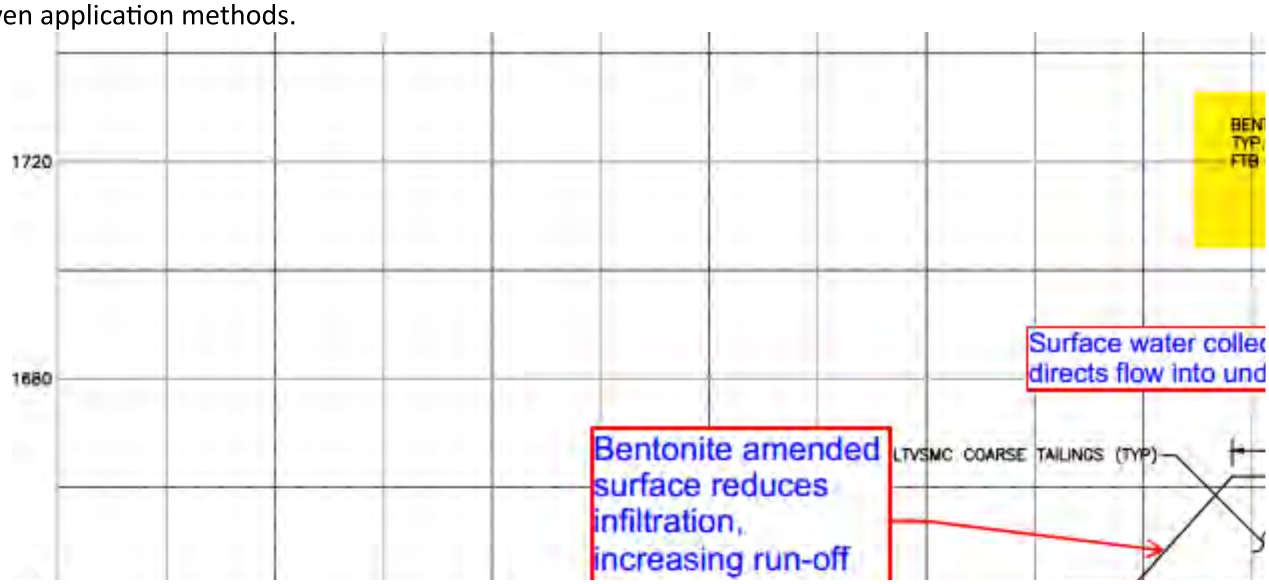
1. As shown on the drawings, (FTB-009) none of us completely understand the function of the 4-foot thick coarse LTV tailings underdrain beneath lifts 1 and 5 along the north face of the embankment. It appears that the underdrain will collect and direct surface run-off into the embankment, potentially saturating the embankment, and reducing the stability. This item requires further explanation and review. (see first image below) We don't think that the purpose of the underdrain is to collect surface water, but that's what is illustrated.

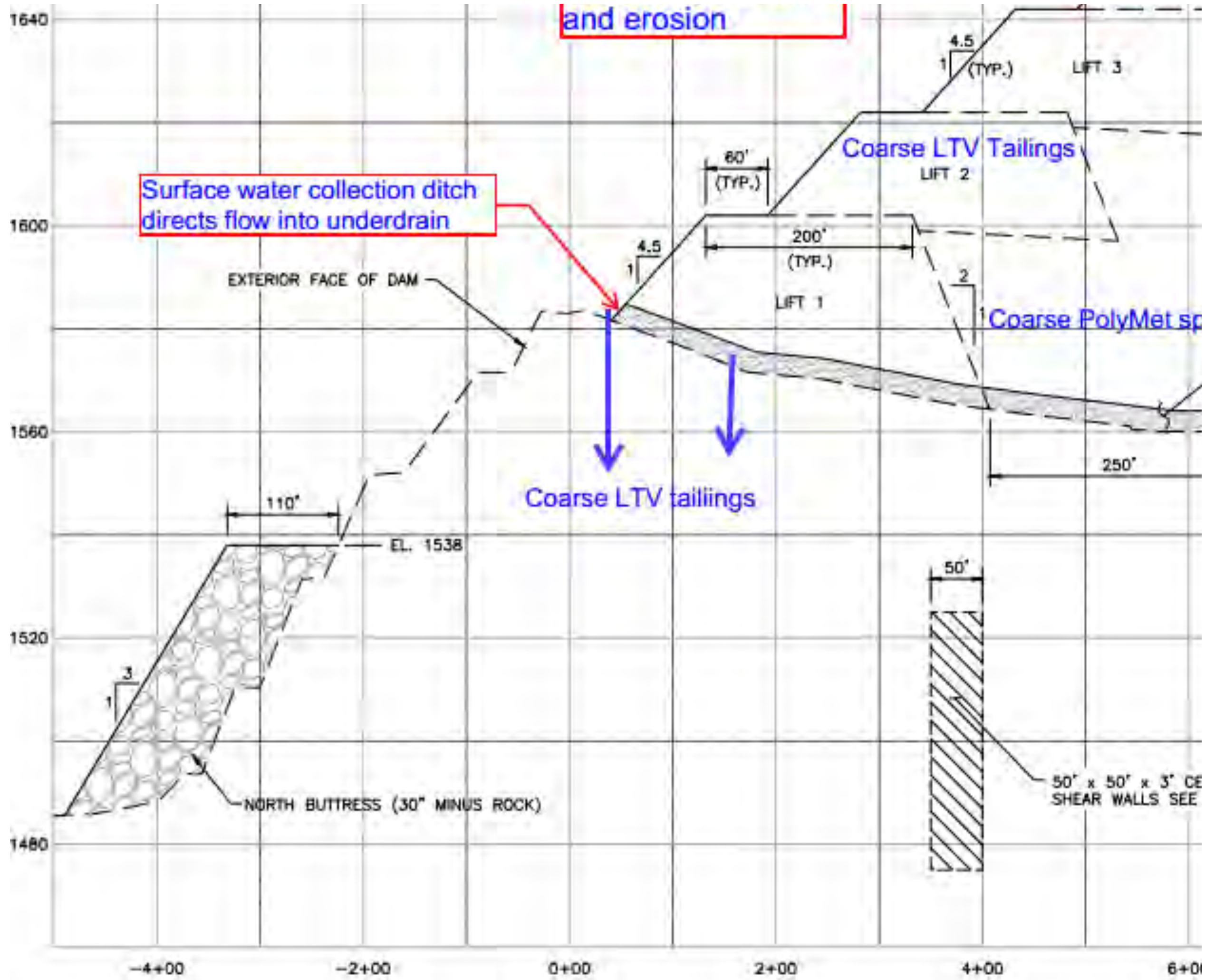
2. I wasn't tasked to look at the dam stability, so don't know if the stability analysis assumed the embankment was saturated or dry. The analysis needs to be done considering rainy wet conditions where the surface run-off is being forced into the embankments. This will shift the phreatic surface closer to the embankment, especially below lift 5. Below, I describe some other scenarios where erosion can alter the phreatic surface assumptions and potentially cause embankment failure. The analysis also needs to be made when the pond is overflowing the spillway and the embankment is saturated. This is the worst case, unless an earth quake occurs at the same time.

3. The stair step FTB embankment sealed with bentonite is geomorphologically unstable and will erode, potentially cutting back into the pooled water, releasing the water and saturated tailings. Initially, surface water will collect in the horizontal ditch/ponds along the toes of lifts 1 and 5, and infiltrate into the embankment via the underdrain and the coarse LTV tailings beneath lift 1. Later, after the bentonite soil erodes from the slopes, the ditches will fill, plugging the underdrain, forcing the water to overflow the bench and cause head cutting in the non-cohesive tailings. If the FTB is to remain as a permanent structure without perpetual maintenance, then I recommend that the embankments be designed using established geomorphologic land reclamation principals. Otherwise there is a high probability that the embankments will eventually fail due to erosion, and catastrophically release the saturated tailings.

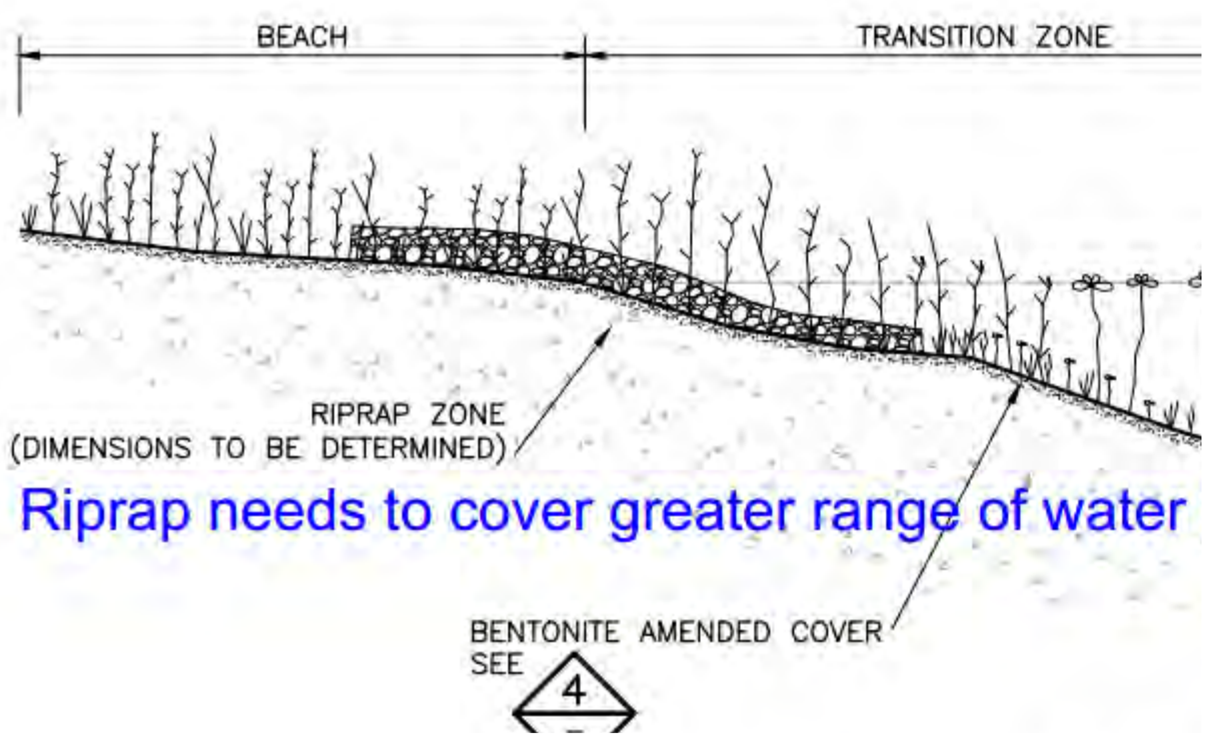
4. As illustrated in Drawing FTB-024, the portion of beach protected by riprap appears to be too narrow, but the width is subject to change. The total extent of the riprap needs to be designed as part of the closure. The size and thickness of riprap need to be justified based on wave action and ice. If the water level fluctuates, wave action could erode above or below the riprap, thus setting up a head cutting scenario from the inside towards the embankment. This could lead to piping and embankment failure. (see second image below). The 625 foot beach slopes 1%, then transitions to a 3% slope to the pond bottom. If the water level drops below the elevation predicted, then the 1% to 3% transition nick point could initiate a head cut that will run back to the embankment. This could trigger piping by allowing water a clear path into the coarse embankment fill when the water level rises. This may not be an issue if the site is perpetually managed and repaired, but will be an issue if the site is abandoned. The water level will not remain constant unless it is managed. If it is not managed, then depending on the bentonite efficacity, the pond could either periodically dry up or over fill. Climate change makes precipitation predictions 100 or 200 years from now impossible, so the design needs to assume the worst case. The range of water level possibilities needs to be addressed in the closure design. If the water level drops lower than designed due to higher infiltration rates or lower precipitation, then the geochemistry assumptions will change as the tailings dry out and oxidize.

The design of the FTB in this permit application will require perpetual maintenance to ensure it will not fail and release the tailings. Placing bentonite on the embankment and interior surfaces will increase the run-off and the erosion rate. The stair-step design is geomorphologically unstable. The methods and assumptions used to place the bentonite to control the infiltration and tailings saturation are unsubstantiated, and wishful thinking. We do not believe it will function as intended, because of the unproven application methods.

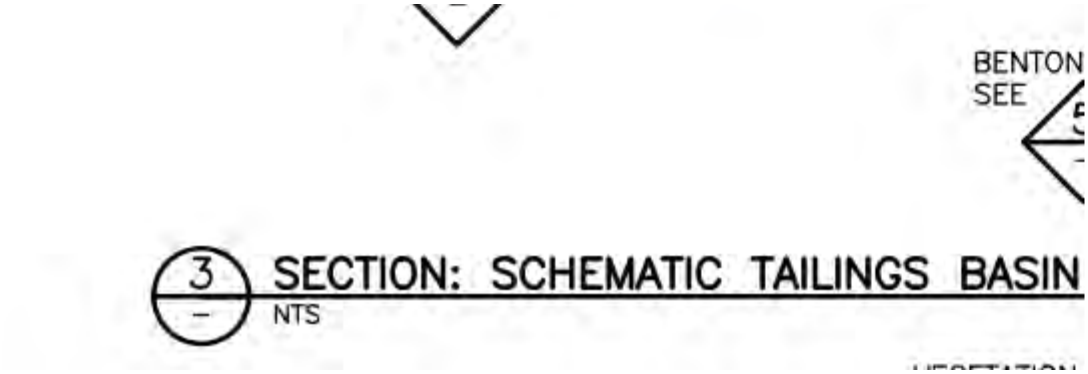




and erosion
Surface water collection ditch directs flow into underdrain
Coarse LTV Tailings
Coarse PolyMet sp
Coarse LTV tailings
EXTERIOR FACE OF DAM
4.5
1
(TYP.)
LIFT 3
60'
(TYP.)
LIFT 2
200'
(TYP.)
LIFT 1
2
1
250'
110'
EL. 1538
50'
3
1
NORTH BUTTRESS (30" MINUS ROCK)
50' x 50' x 3' CE
SHEAR WALLS SEE
1640
1600
1560
1520
1480
-4+00
-2+00
0+00
2+00
4+00
6+0



BEACH
TRANSITION ZONE
RIPRAP ZONE
(DIMENSIONS TO BE DETERMINED)
Riprap needs to cover greater range of water
BENTONITE AMENDED COVER
SEE
4



Donald G. Sutton P.E.
Spectrum Engineering & Environmental
1413 4th Ave. North
Billings, MT 59101
Direct: 406-534-4660
Mobile: 406-670-7270

WL_Dam Permit Comments - Exhibit 16

NorthMet Project - Geotech/Hydromet Mgt Plans [v4; 12/12/2014]
Audit of Permitting-level Information Commitments
Summary 07/05/16 — NOTE: Includes both the Management Plan and Data Package.
Prepared by Bill J. — Yellow highlight is for items identified by PolyMet as being addressed in permitting.

Section	Page(s)	Type	Topic/Commitment	Permit	History
2.1.1	6	Treatment Plant Solids / Coal Ash - Future Waste Characterization	Treatment plant solids and coal ash residue will be characterized prior to disposal in the HRF; if found incompatible with co-disposal with hydromet residue, then alternate management plans will be developed.	Solid Waste	Issue added in v3; no change in v4.
2.1.1	6	Facility Modification	Potential HRF Volume and Height Changes • Bullet 2 (top of page) identifies lime or limestone will be blended with the Residue prior to disposal in the line RHR to address potential for acid generation to exceed neutralizing capacity in the long term. • Approx. 21,000 tpy of limestone or 15,000 tpy of lime, either of which yield an additional 13,000 tpy of additional gypsum for HRF containment. • This is a 4.2% increase in capacity that could be addressed by raising the HRF Phase 3 dam elevation by approximately 3.4 feet. • To be addressed in Dam Safety Review process as detailed in Section 5.4.	Dam Safety	Issue first noted in v2; no change through v4. Notes: • PolyMet/Barr maintain the increase in heigh is insignificant (relative to an 80 foot high structure). • Need to ensure clarity on when the facility is to be constructed relative to this issue (i.e., potential shorter life span).
2.2.1	7	Dam Designs	Dam Construction Materials - Quarried Rock Sourced from Adjoining Hills • It is possible that quarried rock from adjoining hills could be used with soil borrow to construct the dams. • Barr reports rock consists of quartz monzonite and monzodiorite of the Neoarchean Giant's Range batholith, (BJ: basically non-reactive). • Any future bedrock geochemical assays part of Permit to Mine.	Dam Safety Permit to Mine	BJ Note: The issue of inertness appears to be the point of this LAM comment. PolyMet does not see it as an issue for this facility.
2.2.2.1	9	Future Design Changes	PolyMet will consider the relative benefits of alternate liner configurations (during permitting); proposed changes will be held to achieving environmental protection equal to that provided by the proposed double liner system.	State Disposal System Dam Safety Solid Waste Permit to Mine	
4.5	22-23	Winter Operation	Agencies recommend that the winter operations and management plans be reviewed by a cold region mining expert.	Permit to Mine	Note: Barr maintains their team are winter operations experts. If this is to be done independently, will probably need to accomplished by DNR consultant.
5.2	25-26	Monitoring Provisions	Cold Weather & Heavy Precipitation Events: • Agencies identify that more detail be provided on monitoring and management during cold weather and heavy precipitation events. Although not directly noted in the management plan, PolyMet agreed to discuss during permitting.	Dam Safety	DNR Dam Safety noted that while the basin is designed to handle both, it seems that the unexpected type of events occur more frequently during these type of conditions. Possibly incorporate those actions from a similiar basin in an extreme climatic environment. [BJ Note: Not sure what "[p]ossibly incorporate those actions from a similar basin" means; maybe permit conditions already identified for another facility that could be applicable (so that not starting from scratch)?]
5.2			Seepage Collection System: • Agencies identify that the seepage collection system be monitored for freezing and ice build up. The management plan does not anticipate this to be a significant concern, but PolyMet agreed to discuss during permitting.	Dam Safety	First raised in v2; deferred through v4.
6.1		Permitting Requirements	The content requirements for annual reports will be defined during permitting.	Dam Safety Permit to Mine	
7.3.2	35	Cover Design - Final Slopes	Surface Runoff Management - Cell Interior Runoff Slope 1% Grade • PolyMet acknowledges sequencing to final configuration will be necessary. It is predicted that settlement will cease within approximately 10 years after cessation of HRF operations, at which time the final cover will be placed over the temporary cover and positive drainage re-established as needed. • Details of Surface Water Management to be Included in Final Design for Permitting and Construction.	Permit to Mine Solid Waste	First noted in v2; deferred through v4. NOTE: Issue of MPCA interest.
7.3.3	35	Inspection Frequency	Facility Inspection - Annual vs. Semi-Annual • PolyMet proposes a semi-annual inspection frequency after reclamation. • MPCA notes that typically, closed landfills are inspected on a quarterly basis initially. The inspection frequency can be decreased with justification during the postclosure period.	Permit to Mine Solid Waste	First noted in v2; deferred through v4. NOTE: Issue of MPCA interest.
7.3.4	35	Mowing Frequency	Facility Maintenance - Routine Surface Care • PolyMet proposes mowing to prevent tree growth if needed. • MPCA notes that typically landfill cover systems are mowed annually to prevent tree growth. Frequency to be determined as part of permitting.	Permit to Mine Solid Waste	First noted in v2; deferred through v4. NOTE: Issue of MPCA interest.
7.3.4	36	Financial Assurance	Financial assurance will be required for the perpetual maintenance of the HRF dams and appurtenances.	Permit to Mine	First noted in v2; deferred through v4.
Attachment A	40-65	Engineering Drawings	Drawings to be updated during permitting. Most recent drawings in Version 4 (DEC 2014).	Dam Safety	First noted in v2; deferred through v4.
	44	HRF-003	Figure Key - Trees and Power Poles • Agencies note symbols between trees and power poles are too similar; request different symbols. • PolyMet indicates that legend and drawings will be clarified to extent possible in permitting.	Dam Safety	First noted in v2; deferred through v4.
	48	HRF-007	Requested Features - Unimpacted Areas and Known Tailings Disposal Areas • The agencies request for the figure to depict the outline of the HRF to show what areas will not be impacted by the preload. • The agencies request for the figure to show the extent of known tailings disposal areas in the emergency basin and if any to the northwest of the emergency basin. • PolyMet indicates that the requested items will be provided in the next set of drawings.	Dam Safety	First noted in v2; deferred through v4.
	55	HRF-014	Berm Configuration - Impeding Drainage • Berm proposed between the drainage and leakage collection systems could impede flow collection in the drainage sump to the leakage collection system. • PolyMet concurs and proposes to reconfigure the berm to address the issue.	Solid Waste	First noted in v2; deferred through v4. NOTE: Issue of MPCA interest.
	61	HRF-020	Requested Cross-Section - Stormwater Pond on the East Side of the Basin • The agencies note that a proposed stormwater pond on the east side of the (HRF) basin that could result in flow path underneath the liner toward the NW dam. • PolyMet believes that fine sediment accumulation will limit this possibility, however acknowledges that additional pond seepage control could be necessary. • Cross-sectional details and additional seepage controls will be provided in the next set of drawings.	Dam Safety	First noted in v2, with some modification in v3; no change in v4.
			Temporary Cover to the HRF - Potential for Ponding • Review of v2 noted the potential for precipitation on the surface plus that collected in the sand layer of the temporary layer will be routed to the low area on the west end of the HRF, but this area is below the top of the dike elevation. • PolyMet intends to avoid ponding at this site and anticipates installation of drainage channels, modification of top of dike elevations, catch basin and drain pipe installation, or other measures to accommodate the issue. • Details on surface water management at this location to be provided in the next set of drawings.	Solid Waste	First noted in v2, with some modification in v3; no change in v4. NOTE: Issue of MPCA interest.
	63	HRF-022	Surface Water Runoff Controls - Detailed Designs • The agencies note that surface water runoff management is not complete and recommend: 1) a water diversion channel to the north to keep surface runoff from 2W from entering the HRF basin drainage collection system; 2) a drainage capture system for water from the hill to the SW of the basin; and 3) ensuring final design does not route stormwater to the lined areas. • PolyMet acknowledged the issues and proposed for overall surface water management plan to be reviewed and modified as necessary.	Solid Waste	First noted in v2, with some modification in v3; no change in v4. NOTE: Issue of MPCA interest. BJ: Implies a change to overall surface water management plan; not sure if this is a freestanding document.
	64	HRF-023	Closure Inlet Box - Location and Operation • Because pipes are through embankments in closure, appears to be potential for clogging, blockage, or damage to closure inlet box. • PolyMet believes system will operate as proposed, but will provide redundancies with embankment overflow provisions and rip-rapped channels added to designs.	Dam Safety	First noted in v2; no change through v4.
		Cross Section 3	Cover System Precipitation Management - Termination of Granular Drainage Layer • On cross section 3, it is proposed to terminate the granular drainage layer of the final cover system into the dike on the south and east sides of the HRF. This design will not ensure that precipitation that infiltrates the cover system and is collected in the drainage layer will be removed from the lined area of the HRF. • PolyMet intends to avoid ponding water on the cover of the HRF. Necessary details to demonstrate avoidance will be added to the design.	Solid Waste	First noted in v2, with some modification in v3; no change in v4. NOTE: Issue of MPCA interest.
Attachment G	PDF Page 136	Technical Specifications	Water Return Pipe and Residue Discharge System - Insulation • Without insulation any break or disruption could lead to a frozen pipeline, with near frozen water expected at times. • PolyMet defers the issue of whether to insulate the piping to permitting.	Permit to Mine	First noted in v2; deferred through v4.
Attachment K	PDF Page 273	Flowchart	HRF Dam Failure Notification Flowchart needs to be provided.	Dam Safety	
NorthMet Project - Geotech/Hydromet Data Package [v5; 11/26/2014]					
Audit of Permitting-level Information Commitments					
Summary 07/05/16					
Prepared by Bill J.					
Section	**Page(s)**	**Type**	**Topic/Commitment**	**Permit**	**History**
2	4	DNR Approval	QA/QC Plan • The State of Minnesota requires submittal, review, and state approval of a quality assurance/quality control (QA/QC) program for liner systems prior to construction. • Permit issuance for the facility depends on compliance with the approved QA/QC plan.		

6.3.2	56	Future Investigation	Leakage Collection System - Alternative Geomembranes • The HRF liner design assumes that post-construction liner leak location surveys are imperfect and that some defects in the upper geomembrane component of the liner system remain undetected and unrepaired following liner construction. • Recently developed geomembranes facilitate post-construction leak location surveys that are proven capable of detecting all liner ndefects. The defects can then be repaired prior to placing the lined facility into service. • At the point in time when the HRF proceeds to permitting, PolyMet will evaluate recently developed geomembranes as an alternate to the proposed geomembranes, as means by which overall liner configuration can potentially be simplified while still achieving the objective of a virtually leak free HRF.	Permit to Minevice. Solid Waste	Note: This would seem to be of interest to both MPCA and DI

Review and Conference Call Record

Call Date: November 29, 2010
Topic: EPA review of NorthMet Project Flotation Management Plan (FTMP)

Participants:
ERM (third party contractor): Al Tripple, Bec Gawtry, Jeff Coffin
MnDNR: Jennifer Engstrom, Bill Johnson, Dana Dostert, Jason Boyle, Memos Katsoulas, Stuart Arkley
Barr (PolyMet contractors): Tom Radue
USACE: Jon Ahlness
EPA: Stephen Hoffman (HQ), Anna Miller (Region 5 NEPA)

This memo records EPA's review of Flotation Management Plan (FTMP) Northmet Project for Polymet by Barr Engineering, March 18, 2009 and the subsequent the teleconference. The purpose of this document review was to determine if the geotechnical studies were conducted in a sound fashion and to identify areas of concern regarding the engineering stability of the proposed tailing pond. Most of the detailed engineering field analysis and modeling used in the FTMP are found in Appendix A of the FTMP titled Preliminary Geotechnical Evaluation Draft 02 dated March 18, 2009. This memo represents EPA's professional judgment with regard to these matters, and was conducted by Steve Hoffman, in his capacity as a member of EPA's National Hard Rock Mine Team.

Summary of Review

EPA's opinion is that the field studies and modeling conducted by Barr reflect sound engineering practices. The field efforts were conducted in a manner that should provide adequate and sound inputs into failure modeling which was also conducted using a sound engineering approach. EPA's review highlighted several modeling assumptions, and notes that it is important that all the interested parties carefully review the modeling assumptions and model inputs to be assured that there is complete understanding of what the modeling actually speaks to. These studies use factors of safety that should also be assessed to determine if broader public safety and policy concerns are dealt with.

The following are EPA's specific questions and comments after reading the documents. Discussions are noted in italics.

The FTMP indicates that the Polymet tailings pond will dispose 11.27 million short tons annually in Cells 1E and 2 E of the existing LTVMSC tailings ponds. Earlier studies have indicated that the LTV tailings ponds may have elements which are structurally unsound. The FTMP acknowledges that the Polymet project would have to alter the existing ponds to assure that future disposal would be conducted in an acceptable fashion. The Polymet proposed design for the altered tailings ponds includes structurally buttressing embankments, installation of drainage collection systems, and the placement of LTVMSC coarse tailings on the bottom of the cells to serve as a "blanket" prior the placement of new tailings. The basis for the new design is based on Barr Engineering studies which involved the review of prior engineering studies of the LTVSMC tailings pond, coring and boring programs at the site, a broad range of engineering testing on bulk LTV and Polymet tailings, and extensive geotechnical modeling.

Polymet intends to raise the height of embankments (with 20 foot lifts) using the upstream method and use LTVSMC coarse tailings. While the engineering modeling indicates that these tailings do not appear to retain liquid, Stephen Hoffman (EPA) noted concern that this method has inherent risks since embankments are built on top of placed tails. While the Barr Engineering model show that such an approach should be stable under anticipated stress, EPA and the State may wish to discuss whether the State is comfortable in allowing this construction method.

The FTMP notes that there is an existing Coal Ash landfill in the southeast portion of Cell 1E. Barr properly notes that the State must give approval if the landfill can be inundated or relocated. EPA has recently been involved with reviewing the status of coal ash landfills due to the recent history of coal ash landfill structural problems. We recommend that the State and Polymet carefully review this decision, since EPA has found (and supported by the Tennessee Valley Authority (TVA) Kingston failure mode analyses) that coal ash is far less stable and more subject to liquefaction than was previously known.

Modeling uses a Probable Maximum Precipitation (PMP) for 1 square mile of 38 inches during a 72-hour storm. This assumption should be verified as acceptable to the state. Steve would like to see how the 38-inch event compares to the 100-year storm event. If the model assumes a 38-inch event, tables in the report show at 20 years for Cell 1/2 E use 36 inches; the reason for the difference was questioned. Table 3 shows the bounce and peak water surface for the cells throughout the life of the units. The design allows for a freeboard of 5.25 feet. The State needs to consider whether that freeboard value is acceptable.
Discussion: The event in question is a 72-hour storm. The difference in the 36" vs. 38" event reflects different surfaces.

Overall dam construction will be 200 feet at the base with 4.5 H:1V slope on the outside and 2H:1V slope on the inside with 20 foot lifts. The design includes the use of a 60-foot bench from the outside edge of the previous lift to the toe of the new lift. As noted above, the design incorporates significant buttressing of the existing embankments. On page 19, there is a summary of the freeze-thaw issue. Barr noted that since tails will be placed subaqueously, freezing of the unit will not be a problem. EPA was interested in the geotechnical stresses caused by the freezing and thawing the pore waters in the embankment walls, but was not able to determine if such an analysis was conducted.
Discussion: Barr and the State indicated that since embankments are free draining, frost would only be surficial and freezing is not expected. EPA suggested that the assumption that the embankment won't freeze may be part of the State's review of the model assumptions pursuant to the dam permit.

Appendix A Preliminary Geotechnical Evaluation Draft 02

The following section summarizes EPA's review and comments on the bulk of the geotechnical evaluation, which is found in Appendix A Preliminary Geotechnical Evaluation Draft 02; conference call discussion noted in italics.

It should be noted that Barr has conducted a well-rounded, professionally detailed geotechnical evaluation of the existing tailings pond and has conducted modeling of the proposed design following acceptable sound engineering approaches. Modeling was accomplished for multiple cross sections of the embankments. This is a sound approach.

EPA's principle concern with this work relates to the factors of safety used to design the new tailings pond. The modeling uses a liquefaction factor of safety of 1.05. We have previously noted to Polymet our concerns regarding the use of this factor of safety. In previous discussions, State officials noted that model runs have inherent sensitivities and that a calculation of 1.05 may have variances on either side of the point. At the end of the day, the State has permit authority for this unit. It is therefore solely the State's responsibility to determine if it wishes to accept or reject the use of this the 1.05 factor of safety for liquefaction.
Discussion: Steve Hoffman was asked about observations at other sites, and noted that the industry standard, driven by companies, is generally is migrating to a safety factor of 1.50. Steve discussed that this is a technical consideration, but perhaps more so a public policy decision. EPA, however, does not have standards regarding safety factors.

In 2005 Barr conducted stratigraphic analysis of tailings in the central portion of Cell 2W and 1 E. In 2007 Barr conducted geotechnical field investigations at Cells 2W, 2 E and 1 E. Testing included Standard penetration Tests (SPT), drilling and cone penetratrometer tests (CPTu) soundings, dilatometer tests (BMT), vane shear (VST) and seismic shear wave velocity and dissipater testing. Analysis was conducted on both undisturbed and disturbed samples.

Section 2.2.8 presents the results of laboratory testing which was then used as input to modeling. Table 2 shows the analyses of the LTVSMC tails assess blended samples. EPA noted that it is not clear whether testing was conducted using all four mix ratios. Page 2-10 noted that there may be dilative behavior in fine tails. What is that behavior and why is it believed that the behavior may be related to the shipping of samples? Page 2-11 noted that LTVSMC fine tailings were subjected to peak and contract slights and that they subsequently began to dilate under loadings. What does this finding mean?
These studies assume that the Polymet and LTVSMC tailings will liquefy and the modeling assumes conservative values (as noted in (3.7). EPA suggests that the State determine whether these values are acceptable for their permitting process.
Discussion: Barr (others?) believe the tests were conducted on mixed ratios, but will reconfirm. Contraction from sharing was expected for fine tailings. Dilation was assumed to indicate that the lab sample had been disturbed.

In Section 3.1 as previously noted, the design incorporates the use of a foundation

mat tied into the upstream toe of the first LTVSMC lift. The design of the tie-in was discussed, and EPA recommended to the State that this design feature be modeled for its stability under stresses, which would provide the State additional information about the stability of the proposed approach.
Discussion: The mat was modeled for stress; EPA suggested adding that information into future design or permit documents .

The modeling noted in Section 3.3 used circular and sedge failure methods. Using both these methods is a good approach.

As noted in Section 3.4 a factor of safety of 1.5 was targeted; however , other factors were used in this evaluation. It appears that a USAA liquefaction strength factor of 1.05 was used throughout the document. EPA would be interested in knowing the State position the safety factor.

Seismic evaluations noted in Section 3.5 are acceptable.

In Section 3.6 Liquefaction potential, the design of the dams was modeled during a steady state undrained condition. Did this modeling also include modeling under a rapid draw down condition?
Discussion: The dam was not modeled for rapid drawdown, but Barr did prepare a drained shear strength test. Steve noted that a lot of work (projects) now do model the rapid draw down; he suggests s walking people through the rationale of not doing one.

Please confirm that Table 12 in Section 3.7.27 presents the undrained yield strengths of the Polymet tailings.

What is the state position on Table 5 Index Properties Postulates and Table 6 Permeability Postulates?

In Section 3.7.27 Polymet Bulk tailings analyses uses 3 representative values of permeability (6.23 x 10^{-6} ft/sc under 0.45 TSF, 1.84x10^{-6}ft/sc under 1.35 TSF, and 6.56x10^{-7} ft/sc under 2.79 TSF. EPA's Steve Hoffman agrees that such ranges of permeability should be used, and highlights that the State needs to determine whether it agrees with these representative values.

In Section 3-23 these studies assume a range of values for the compressibility of tails. Steve agrees that the laboratory tests on the LTVMSC coarse tails do indicate that they appear to have good compression. Does the state agree with this conclusion?

In section 3.7.4.7 Polymet CIU study it appears that data came from one sample however a range of peak and liquefied undrained shear strength ratios were used based on actual values from the triaxial testing. What is the state position on this approach?
Section 3.76 Shear Strength Parameters Summary-Does the state agree with the use of these parameters?

Section 4.4 models use variability in permeability of till. This is a god approach. Section 4 notes that the tailings location has a complex stratigraphy and hydraulic conditions can be very difficult to match in modeling. Seepage can vary 5-10 feet in this area. If this is the case how did the analyses address this uncertainty? EPA suggests that the State may wish to look at a probabilistic approach.
Discussion: Section 4 discusses model calibration, and a whether the conductivity value was conservative. An alternative to probabilistic modeling could be that the applicant provides a clear written explanation on how the uncertainty was handled.

Table 23 notes that the USSA liquefaction results for Year 20 for Section F is 1.1 and for wedge 1.055. What is the variability within the model runs?

Appendix E notes the location of the test locations. The number and location of these tests appears adequate.

Summary thoughts from EPA:

- *EPA suggests that the geotechnical IAP workgroup review Appendix J Liquefaction Potential and Strength Parameters since this effort is a key input into broader modeling.*
- *EPA notes that the State needs to review the Table 22 modeling parameters since these factors are the heart of model results.*
- *Existing data is good enough to rerun models using other safety factors and assumptions.*
- *EPA notes that the decisions on the tailings basin can be more than a model or engineering results – safety factors must be decided upon, and then communicated clearly.*

Steve Hoffman, EPA, may be reached at 703-308-8413.

Dana's recommended direction on Polymet
February 23, 2011 (9:19am)

1. DNR should accept the 1.20 value as the acceptable Factor of Safety for Liquefaction (FS_{Liq}). This is the recommended value from the MSHA "2009 Engineering and Design Manual, Coal Refuse Disposal Facilities" (EDM). There are several additional sources that recommend the 1.20 value, including internal DOW Dam Safety guidance documents. This FS_{Liq} should be applicable for both seismic events and pore water pressure.

2. In cases where the applicant cannot meet the FS_{liq} of 1.2, the applicant should complete the methodology as described in the MSHA 2009 Engineering and Design Manual.

   a. Consider changes to cross section design
   b. Perform the appropriate deformation analysis on the basin.
   c. Perform seismic, vibration and cyclic tests on basin (earthquake, trains and plant vibrations)
   d. Perform trigger tests on basin.
   e. Perform a probability of failure analysis.
   F. Perform a long term deformation analysis.

3. Upon receipt of the above analysis, Dam Safety should determine if additional tests are needed or if the analysis is complete. If complete and the analysis shows no failure or significant deformation of the containment dams, we should issue the permit. If the analysis shows major or significant deformation of the basin, or a high probability of failure in either the short-term or long-term, we should deny the permit until the basin is redesigned and can meet the required criteria.

4. The existing Cell 1E dam should have a minimum FS_{Liq} of 1.20 on the southwest side of the cell as it's close proximity to the plant, higher traffic areas, rail lines and offloading site, and the hydromet facility (if built), increase the risk for personal injury or loss-of-life.

5. We should have Knight-Piesold and ERM comment on this position. After comments and suggestions are received, we should write Polymet/Barr and inform to proceed with the analysis requested.

Geotechnical Stability Impact Assessment Planning Summary Memo
NorthMet Project EIS
May 18, 2011

Introduction

The Minnesota Department of Natural Resources (MDNR), US Army Corps of Engineers (USACE), and US Forest Service (USFS), collectively known as the Co-lead Agencies, have prepared this guidance memo as the concluding step in the impact assessment planning (IAP) process for this subject area. This memo provides: (1) a summary of workgroup issues considered; and (2) specific guidance to PolyMet Mining and its consultants that is to be incorporated into a work plan for Co-lead Agency review and approval prior to conducting impact analysis (i.e. modeling and other predictive work) on the Draft Alternative Summary as amended March 4, 2011.

Workgroup Facilitators
Bill Johnson and Stuart Arkley, MDNR ECO
Al Trippel, ERM

Workgroup participants included those persons listed in Attachment A.

Impact Assessment Requirements of the Draft Alternative

The facilitators worked closely with MDNR Dam Safety and Lands and Minerals, along with USEPA Region 5, to review the stability analysis methods used in 2009 DEIS, and modify upcoming analysis of the Tailings Basin and Hydrometallurgical Residue Facility designs to be included in the Supplemental DEIS.

Tailings Basin and Hydrometallurgical Residue Cells

- The Draft Alternative for the Tailings Basin should be modeled as was done previously for the DEIS, with additions that are described below. Baseline investigation and analysis information used in the DEIS are adequate to support the new modeling.

  The existing GeoStudio modeling needs to be modified to include the proposed bentonite amended layer (exterior face of new dams and NorthMet tailings beaches) and bentonite enhanced permanent pond bottom. Some additional analysis of the modeling parameters is also requested. In addition, Dam Safety has requested that an additional cross section be created and analyzed for the southwest corner of cell 1E, at the site of a piping failure in the mid-1980s. This additional analysis does not need to be completed for the IAP, but should be completed within two years of construction start up.

- Factor of Safety (FS) - Proposed methodology for further analysis:

  FS should meet or exceed: 1.50 ESSA[1] (drained); 1.30 USSA[2] (undrained) for non-statically liquefiable materials; and 1.20 for seismic and static liquefaction. If material properties and distributions are well defined, the factor of safety for static liquefaction can be reduced to 1.10 (Poulos, S.J., Castro, G. and France, J. W., 1985. Liquefaction Evaluation Procedure). If FS meets

[1] ESSA - Effective Stress Stability Analysis
[2] USSA – Undrained Strength Stability Analysis

or exceeds these values, that cross section is complete and further analysis of that cross section will probably be unnecessary, pending results of the analysis.

- Drained and Undrained conditions – If a FS for the drained or undrained conditions does not meet or exceed minimums, a redesign or modification of that cross section will be required.
- Seismic liquefaction – Perform a Probabilistic Seismic Hazard Assessment for the site to estimate potential seismic events. Using these estimated events, evaluate seismic liquefaction potential using industry accepted commercial computer software. These results can then be used to assess material properties (post liquefaction shear strength of materials shown to liquefy) and pore pressure conditions to be used in post event stability analyses with a minimum FS of 1.2.

  If liquefaction, and therefore large material shear strength reductions, does not occur, perform a deformation analysis using pseudo static techniques which are industry accepted.
- Static Liquefaction – If the FS for static liquefaction is below 1.20 and the material properties are not well defined, further analysis is needed. This analysis includes determining if static liquefaction can be triggered. If the factor of safety for triggering liquefaction meets or exceeds 1.50, no further analysis is needed. If neither of these conditions can be met, the embankment will need to be modified or redesigned. Further analysis of the liquefied shear strength parameter ($USSR_{liq}$).[3] is needed as that value appears to be higher than typically observed.

- A geotechnical analysis of the new Hydrometallurgical Residue Facility design needs to be undertaken. This analysis will be different than the analysis of the Tailings Basin because of the different embankment configurations. The Hydrometallurgical Residue Facility design should include typical methodologies used to analyze a lined storage facility, such as an effective stress stability analysis, analysis of foundation conditions (including baseline hydrological conditions), and an analysis of the liner integrity. MPCA will also have permit authority of the Hydrometallurgical Residue Facility under their solid waste and water discharge rules, and the DNR's Permit to Mine will need to include information on the hydrometallurgical residue facility design.

- The work plan for the Hydrometallurgical Facility will state that the analysis of stability include a detailed accounting of existing baseline water sources at the site, including surface discharges from the surrounding highlands, subsurface movement of water through the buried stream channel, and/or springs that may still discharging water at the site.

<u>Waste Rock Stockpiles</u>

The approach to Waste Rock Stockpile stability analysis for the designs in the Draft Alternative will be the same as used for the 2009 DEIS. Design and construction of the Waste Rock Stockpiles will be required to conform to the criteria established in Minnesota Rules for the Permit to Mine.

[3] $USSR_{liq}$ – Liquefied Undrained Shear Strength Ratio

Report(s) Preparation
Separate reports are requested for the geotechnical analysis of the Tailings Basin, Hydrometallurgical Residue Facility, and the Waste Rock Stockpiles.

In each report, describe what will be built, where, and how with sufficient detail and clarity. Show baseline conditions of the existing LTVSMC Tailing Basin. Show that the embankments will be stable during construction and post-closure, and that conservative assumptions, parameters, and inputs were used. Provide a table showing all model input parameters, along with the range of values of the parameter and the sources/test/number of samples used to determine the value. Include a discussion of the long term post-closure period regarding stability of these facilities over time.

Key Issues and Decisions
For the Tailings Basin, MDNR Dam Safety revisited its requirements and the site specific conditions at the NorthMet Project and concluded that the design should meet or exceed a factor of safety of 1.20 for seismic and static liquefaction, unless supported by additional information/analysis as specified above.

ATTACHMENT A

NorthMet EIS Geotechnical IAP Participant List

Workgroup Participants

Stuart Arkley (MDNR ECO)
Bill Johnson (MDNR ECO)
Dana Dostert (MDNR Waters – Dam Safety)
Jason Boyle (MDNR Waters – Dam Safety)
Memos Katsoulis (MDNR LAM)
Jennifer Engstrom (MDNR LAM)

Jon Ahlness (USACE)
Neil Schwanz (USACE)
Tom Hingsberger (USACE)

Tom Hale (USFS)

Stephen Hoffman (USEPA HQ)
Anna Miller (USEPA R5)

Richard Clark (MPCA)

Rose Berens (Boise Forte Band)

Margaret Watkins (Grand Portage Band)

Nick Axtell (1854 Treaty Authority)

John Coleman (GLIFWC)
Esteban Chiriboga (GLIFWC)

Al Gipson (KP / ERM)
Jeff Coffin (KP/ERM)

Tom Radue (Barr)
John Borovsky (Barr)

Jim Scott (PolyMet)

Boyle, Jason (DNR)

From: Tom Radue [TRadue@barr.com]
Sent: Monday, January 14, 2013 9:54 AM
To: Boyle, Jason (DNR)
Subject: PolyMet Follow-Up

Jason – this E-mail is just to reiterate PolyMet's position re. Tailings Basin Slope Stability Analysis as we discussed in brief last week:

- The March 2012 NorthMet Geotechnical Modeling Work Plan required that four sets of slope stability analysis be performed:
  - ESSA – Required Slope Stability Safety Factor ≥ 1.5
  - USSA – Required Slope Stability Safety Factor ≥ 1.3
  - Liquefied Analysis (triggering) – Required Slope Stability Safety Factor ≥ 1.2
  - Liquefied Analysis (fully liquefied) – Submitted for Information Purposes

- Slope stability analysis findings presented in Geotechnical Data Package – Volume 1 – Version 3 indicate:
  - ESSA – Required Slope Stability Safety Factors are met or exceeded.
  - USSA – Required Slope Stability Safety Factors are met or exceeded.
  - Liquefied Analysis (triggering) – Required Slope Stability Safety Factors are met or exceeded.

- PolyMet is receptive to completing the sensitivity analysis on USSA as outlined in the March 2012 Work Plan.

- Since the Liquefied Analysis (triggering) shows that triggering of full liquefaction will not occur, PolyMet is not receptive to performing sensitivity analysis on the Liquefied Analysis (fully liquefied). Instead, and although clearly beyond the scope of the current Work Plan, PolyMet would be receptive to performing further sensitivity analysis on the Liquefied Analysis (triggering).

I hope this adequately summarizes PolyMet's opinion regarding further slope stability analysis. I'll plan to call you later today to discuss current status on this.

Best regards,

Tom

Tom Radue, P.E.

Vice President
Senior Geotechnical Engineer
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tradue@barr.com
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CHAPTER III

GRAVITY DAMS

March 4, 2016

the interface could resist tension, the rock formation immediately below may not be able to develop any tensile capacity. Therefore, since stability would not be enhanced by an interface with tensile strength when a joint, seam or fracture in the rock only a few inches or feet below the interface has zero tensile strength, no tension will be allowed at the interface.

3-5.2.3 Sliding Stability Safety Factors

Recommended factors of safety are listed in table 2 and 2A.

TABLE 2
Recommended Minimum Factors of Safety 1/
Dams having a high or significant hazard potential.

Loading Condition 2/	Factor of Safety 3/
Usual	3.0
Unusual	2.0
Post Earthquake 4/	1.3

Dams having a low hazard potential.

Loading Condition	Factor of Safety
Usual	2.0
Unusual	1.25
Post Earthquake	Greater than 1.0

Notes:

1/ Safety factors apply to the calculation of stress and the Shear Friction Factor of Safety within the structure, at the rock/concrete interface and in the foundation.

2/ Loading conditions as defined in paragraph 3-3.0.

3/ Safety factors should not be calculated for overturning, i.e., M_r / M_0.

4/ For clarification of this load condition, see paragraph 3-4.4.

For definitions of "High", "Significant", and "Low" hazard potential dams, see Chapter 1 of this guideline.

One of the main sources of uncertainty in the analysis of gravity dam stability is the amount of cohesive bond present at the dam foundation interface. The FERC recognizes that cohesive bond is present, but it is very difficult to quantify through borings and testing. It has been the experience of the FERC that borings often fail to recover intact interface samples for testing. In addition, strengths of intact samples that are recovered exhibit extreme variability. For this reason, table 2A below offers alternative recommended safety factors that can be used if cohesion is not relied upon for stability.

TABLE 2A
Alternate Recommended Minimum Factors of Safety
for Use in Conjunction with a No Cohesion Assumption

Loading Condition	Factor of Safety
Worst Static Case 5/	1.5
Flood if Flood is PMF 6/	1.3
Post Earthquake	1.3

Notes:

5/ The worst static case is defined as the static load case with the lowest factor of safety. It shall be up to the analyst to determine the worst static case and to demonstrate that it truly is the worst static case.

6/ Because the PMF is by definition the flood that will not be exceeded, a lower factor of safety may be tolerated. Therefore if the worst static case is the PMF, a factor of safety of 1.3 is acceptable. If the IDF is not the PMF, then the safety factor for the worst static case shall control.

The factor of safety is the ratio of actual shear plane resistance to the shear plane resistance that would allow the initiation of sliding. It is not a ratio of forces, but rather a demand capacity ratio. For example, in a friction only analysis:

$$FSS = \frac{Tan(\phi_{actual})}{Tan(\phi_{reqd})}$$

SPECTRUM ENGINEERING

To: Jennifer Engstrom, MDNR
From: Donald Sutton
Date: February 24, 2012
Subject: HydroMet and Stockpiles - review of Barr responses to comments

PolyMet Geotechnical Modeling Work Plan comments

Flotation Tailings Basin Geotechnical Model for SDEIS, FEIS and Permitting:

1. Item 3a. The bentonite seal is a hail Mary type of concept in my opinion. I believe it will exacerbate erosion and slope failure and will eventually fail, so I recommend that the stability analysis should assume the bentonite doesn't prevent seepage so far as stability is concerned.
    a. What is the stability of the side slopes if a layer of tailings is placed above the bentonite and it becomes saturated? Will the bentonite slope fail?
    b. What if the bentonite slope is saturated and there is an earthquake or a thunderstorm?
2. I am concerned about long term climate change and how it will affect the water balance in the tailings facility because this can affect the water level, the water head, the saturation, and most importantly, erosion.

    Erosion can cause the shape of the embankments to change over time, it can cause erosion and gullying that can create a pathway for water to escape from the pond. This bothers me, because the proposed design is temporary and will fail unless it is perpetually maintained. I am surprised that the Minnesota statutes allow a temporary impoundment structure to be permitted permanently. This wouldn't be allowed in other jurisdictions. I realize that this will be addressed during the permitting and financial assurance review. Estimating the liabilities will be contentious.

Stockpile Geotechnical Models for SDEIS, FEIS and Permitting:

1. Is there a schedule for collecting the foundation data? How does it relate to the EIS if the data isn't obtained in time?
    a. As a practical matter, I think the stockpile geotechnical designs pose no geotechnical EIS related concerns provided they honor the statutes. My concerns are related to water management, erosion control and geochemical issues.
    b. There is a potential minor leak risk with the liners, but this is minimal and has been addressed. I would like to see the sub-base designed so that any leakage can be collected or directed to the pit pumping system. At some point, someone needs to check this, but it isn't a geotechnical item.

1413 4th Avenue North • Billings, Montana 59101 • 406/534-4660 • Fax 406/259-1456 • sutton@spectrum-eng.com

DRAFT

DNR Review of PolyMet's Dam Safety - HydroMet Facility - Permit Application

Reviewers: Steve Gale/Nate Lichty - Gale Tec Engineering, Inc., Dirk Van Zyl and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

Priority Rankings:

1 - Proposed Requirements (critical or high importance issues): Permit is not recommended to be issued until these items are resolved either by incorporating the proposed changes or by providing more information.

2 - Proposed Recommendations: Recommended additions/changes, but not requirements to the permit application.

Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
1	Management Plan - page 10	Section 2.2.2.2	This 80 foot high residue storage facility will be constructed over potentially soft ground. The management plan addresses shear strength gain and settlement of the soft soils but does not commit to a construction plan stating that the Observational Method will be used to assess what type of construction needs to take place in the future. Since the soft foundation soils already exist in place, these soils should be further tested and further evaluated such that a design can be promulgated. The pre-load method should be evaluated and a determination made if the pre-load will induce shear strength gain of the soft deposit and whether external drainage, such as wick drains, would be required. It is our opinion that the Observational Method requires a design be presented at the time of Permit application.	1			
2	Management Plan - page 8	Section 2.2.2.1 - Liner and Leakage Collection System Design	The HydroMet residue basin will consist of a double liner with an internal leakage collection system. Since this system is susceptible to rupture as a result of strains in the geomembrane or geosynthetic liner as a result of settlement or other localized conditions, we recommend that the pre-load/wick drain system be further evaluated and a design promulgated for review during the permit application process.	1			
3	Management Plan - page 33 and 34	Section 7.2.2	The management plan identifies that the HyroMet closure will include a 40 mil LLDPE membrane or a MPCA approved geomembrane and a geosynthetic clay liner (GCL) constructed over a working platform. As far as we know, the MPCA does not have an approved geomembrane list. They do have a guidance on their website. We recommend that the liner type be further investigated and the proposed liner be identified and detailed at the time of Permit application	1			

What is needed to make HRF Document Complete?

DRAFT

DNR Review of PolyMet's Dam Safety - HydroMet Facility - Permit Application

Reviewers: Steve Gale/Nate Lichty - Gale Tec Engineering, Inc., Dirk Van Zyl and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

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Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
2	Management Plan - page 10 Geotechnical Report - page 75	Section 2.2.4 - Dam Construction Section 6.3.2.4 - Cement Deep Soil Mixing Zone	Cement deep soil mixing (CDSM) shear walls are shown to be needed to satisfy stability of the north tailings dam as a result of liquefaction of buried slimes. The Geotechnical Report text states that a Construction Quality Assurance Plan will be developed. Since this CDSM structural feature is such a critical aspect of the plan, we recommend that the permit require bench-scale testing, test columns and field validation using such techniques as coring and wet sampling and geophysical testing (i.e. Ps logging and/or electromagnetic testing methods). The Federal Highway Administration (FHWA) has a design manual for Deep Mixing for Embankment and Foundation Support - October, 2013. This manual includes guidance for CDSM installation and integrity testing.	1			
3	Geotechnical Report - page 8 Peat Geotechnical Report - page 41	Tailings Basin Development Section 5.2.3 - Shear Strength of LTVSMC Tailings & Table 5-10	The Report describes various peat layer thicknesses and various slime layer thicknesses beneath the Cell2E North perimeter dam. Sitka Corporation identified typical standard penetration resistance value (blow/foot) for the slimes was 5 or less and for the fine tailings was in the range of 15-20. We recommend that the layer thicknesses and the continuity of the layers be further investigated and a sensitivity analysis be performed based on the thickness, continuity and the liquefied shear strength values. A USSR liq=0.10 is included in Table 5-10 (page 41) for the LTVSMC fine tailings/slimes and further alludes to this value being a minimum to be used for design by the Engineering and Design Manual - Coal Refuse Disposal Facilities published by U.S. Department of Labor - MSHA. Further documentation should be provided for this value: and a sensitivity analysis should be performed in conjunction with the previously described parameters. Sitka Corporation found remolded vane shear strength values of the slimes to be in the range of 100 - 300 pounds per square foot. These low remolded vane shear strength values could indicate a USSR liq. less than 0.10. These lower values could result in a factor of safety of less than 1.1.	2			

DRAFT

DNR Review of PolyMet's Dam Safety - Tailings Basin - Permit Application

Reviewers: Steve Gale/Nate Lichty - Gale Tec Engineering, Inc., Dirk Van Zyl and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

Priority Rankings:

1 - Proposed Requirements (critical or high importance issues): Permit is not recommended to be issued until these items are resolved either by incorporating the proposed changes or by providing more information.

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Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
1	Geotechnical Report- page 123 Management Plan - page 5 Management Plan - page 34	Section 9 - Operation and Maintenance Requirements Section 2.1- Flotation Tailings Characterizations Section 6.3 - Adaptive Management	The Management Plan calls for the design and/or the operation to be modified based on operational experience using the Observational Method. We recommend that this approach be defined in the Permit similar to that included in a paper "Liquefaction of Tailings Dams" by Solseng, P.B. - Barr Engineering Company presented/published for a "Liquefaction of Mining Tailings" symposium in Cleveland, Ohio - 1997. The Barr paper details that the Observational Approach Method concept design should include: 1) Predict behavior with detailed calculations, 2) design with contingencies, 3) construct with monitoring and 4) compare measurements with predictions and redesign if necessary. The Geotechnical Report Section 2.1-page 5 states that this method is used for all MDNR-Permitted Tailings Basins. If the Observational Approach is to be permitted, we recommend that the plan include a design at the time of permitting and identify what instrumentation will be installed, where the instrumentation will be installed and what the instrumentation will monitor (i.e. excess pore water pressures and tailings dam deformations). If the Observational Method is permitted, we recommend that the permit require stability evaluations be submitted at least yearly with the annual Dam Safety Report. If a significant design change is required, we recommend that the company apply for a permit amendment.	1			

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Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
9	Geotech Data Package, Vol. 1, Attachment C, page 19	Section 3.0 - Drained Shear Strength Parameters	The shear strength data for the different materials was evaluated by considering laboratory shear strength data plus interpreted field shear strength data from various tests as appropriate. The 33rd percentile of the resulting data was then selected for the stability analyses. In the case of the drained shear strength of the LTVSMC coarse tailings the shear strength ranges were: laboratory testing 28 to 47 degrees, SPT testing 26 to 50 degrees and CPT testing 39 to 46 degrees (outliers below 39 degrees, to as low as 32 degrees were excluded, Figure A-3). The resulting value selected for stability analysis from the statistical analysis is 38.5 degrees. This value seems on the high side as lab testing and SPT testing values of the high 20's are included in the evaluation while lower values of the CPT testing were excluded. Furthermore, the drained shear strength selected for the coarse tailings is higher than that selected for glacial till - typically a well graded material that is very dense. The angularity of the coarse tailings particles might have played a role in the higher value. However, it is recommended that the stability analysis should also be done with a lower shear strength value, say 36 degrees, for the coarse tailings as part of a sensitivity analysis of the coarse tailings. It is recognized that this may not change the outcome very much, however this sensitivity analysis is an important aspect of developing further confidence in the effective strength stability results.	2			
10		Section 7.2 - Final Reclamation	PolyMet is proposing a 20 year mine life and "wet closure" design for the tailings basin. PolyMet's proposed design is permittable and if permitted, would need to be managed in compliance with all rules and regulations including financial assurance. If permitted, the DNR should also require PolyMet to continually review the current state of practice for design techniques prior to starting any tailing basin closure activities. Information should be reviewed to inform the decision on the best closure design option at the actual time of mine closure, taking into account environmental protections and long term cost of operation. Continued study of tailings basin closure designs should also be considered as a permit condition. If a closure design change is required in the future, it must meet all environmental review and permitting requirements.	TBD			

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Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
7	Geotechnical Report - page 90	Section 6.6.1 - Range and Distribution of Shear Strength Values	The Report identifies that sensitivity analyses were performed for the USSR properties for most of the soils using either a normal or log-normal distribution. However, a sensitivity analysis was apparently not performed for liquefied shear strength ratio (USSR) for the slimes. The Report identifies that based on previous geotechnical workshops, a single estimate of that particular strength was chosen. Apparently, the chosen ratio is 0.10. Using this ratio, 40 feet of overburden would result in a liquefied shear strength of 600 pounds per square foot. Residual vane shear testing has shown slime values as low as 100 - 300 pounds per square foot, which would result in a ratio of less than 0.10. We recommend that this issue be further explored.	2			
8	Management Plan - page 37	Section 7.2 - Final Reclamation	The Plan identifies approximately 3% bentonite by dry weight to be added to the fine tailings beach to a depth of 18 inches and then overlain by 30 additional inches of tailings and then vegetated. The 3% by dry weight addition must be further investigated based on field trials, not laboratory testing in which very controlled conditions exist. Closure of the pond bottom refers the Geotechnical Report reader to the Adaptive Water Management Plan - Version 7. The effectiveness of injecting bentonite through the pond water is subject to concern with regard to reliability of the infiltration reduction.	1			

Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
4	Geotechnical Report - page 8	Section 3.2 - Tailings Basin Development	The Report describes a layer of peat over a deposit of glacial till beneath the Cell 2E North perimeter dam. During the retreat of the glaciers approximately 10,000 years ago, numerous depressions were formed in which lacustrine clay and peat were deposited. The Geotechnical Report, however, does not reference any lacustrine clay layers, only peat over glacial till. Table 5-24 (page 64) identifies peat with a USSR yield = 0.23. This value may be appropriate for a fibrous peat but not for a decomposed amorphous peat or a high plasticity lacustrine clay. The soil types should be further investigated and sensitivity analysis be performed for a range of shear strengths. Geotechnical Report - page 49, Section 5.4.2.2, states that previous testing by Sitka resulted in higher permeability values for peat than that obtained from samples during the most recent 2014 investigation. Such may indicate a different type of peat at various locations.	2			
5	Management Plan - page 22-24	Section 4.2 - Transport and Deposition Plan	It appears that the stability analysis was based on maintaining a beach length of 625 feet between the inside crest of the dam and the edge of the water within the tailing basin. The water pool could, at sometime during the operation, be closer to the dam than the 625 feet. Stability and exit seepage should be evaluated considering the water pocket pool closer or in contact with the tailings dam.	1			
6	Management Plan - page 34	Section 7.3 - Structure Removals	The Management Plan is vague regarding abandonment of existing structures within the tailings basin and assumes that the previous owner properly abandoned all pipes within the basin which could be a conduit for water which could create erosion conditions which could then act as a trigger for liquefaction and induce a flow failure. Specifically, the 9 foot diameter drop inlet decant structure constructed in Basin 2W and the approximate 2000 lineal feet of 40 inch diameter spiral pipe extending into Basin 1E should be addressed and specific actions determined.	1			

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DNR Review of PolyMet's Dam Safety - Tailings Basin - Permit Application

Reviewers: Steve Gale/Nate Lichty - Gale Tec Engineering, Inc., Dirk Van Zyl and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

Priority Rankings:

1 - Proposed Requirements (critical or high importance issues): Permit is not recommended to be issued until these items are resolved either by incorporating the proposed changes or by providing more information.

2 - Proposed Recommendations: Recommended additions/changes, but not requirements to the permit application.

Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
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Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
2	Management Plan - page 10 Geotechnical Report - page 75	Section 2.2.4 - Dam Construction Section 6.3.2.4 - Cement Deep Soil Mixing Zone	Cement deep soil mixing (CDSM) shear walls are shown to be needed to satisfy stability of the north tailings dam as a result of liquefaction of buried slimes. The Geotechnical Report text states that a Construction Quality Assurance Plan will be developed. Since this CDSM structural feature is such a critical aspect of the plan, we recommend that the permit require bench-scale testing, test columns and field validation using such techniques as coring and wet sampling and geophysical testing (i.e. Ps logging and/or electromagnetic testing methods). The Federal Highway Administration (FHWA) has a design manual for Deep Mixing for Embankment and Foundation Support - October, 2013. This manual includes guidance for CDSM installation and integrity testing.	1			
3	Geotechnical Report - page 8 Geotechnical Report - page 41	Tailings Basin Development Section 5.2.3 - Shear Strength of LTVSMC Tailings & Table 5-10	The Report describes various peat layer thicknesses and various slime layer thicknesses beneath the Cell2E North perimeter dam. Sitka Corporation identified typical standard penetration resistance value (blow/foot) for the slimes was 5 or less and for the fine tailings was in the range of 15-20. We recommend that the layer thicknesses and the continuity of the layers be further investigated and a sensitivity analysis be performed based on the thickness, continuity and the liquefied shear strength values. A USSR liq=0.10 is included in Table 5-10 (page 41) for the LTVSMC fine tailings/slimes and further alludes to this value being a minimum to be used for design by the Engineering and Design Manual - Coal Refuse Disposal Facilities published by U.S. Department of Labor - MSHA. Further documentation should be provided for this value: and a sensitivity analysis should be performed in conjunction with the previously described parameters. Sitka Corporation found remolded vane shear strength values of the slimes to be in the range of 100 - 300 pounds per square foot. These low remolded vane shear strength values could indicate a USSR liq. less than 0.10. These lower values could result in a factor of safety of less than 1.1.	2			

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DRAFT

DNR Review of PolyMet's Dam Safety - HydroMet Facility - Permit Application

Reviewers: Steve Gale/Nate Lichty - Gale Tec Engineering, Inc., Dirk Van Zyl and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

Priority Rankings:
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2 - Proposed Recommendations: Recommended additions/changes, but not requirements to the permit application.

Number	Page	Section or Table Number	Comment/Concern	Priority Ranking	Reviewer	Date Discussed	PolyMet Response
1	Management Plan - page 10	Section 2.2.2.2	This 80 foot high residue storage facility will be constructed over potentially soft ground. The management plan addresses shear strength gain and settlement of the soft soils but does not commit to a construction plan stating that the Observational Method will be used to assess what type of construction needs to take place in the future. Since the soft foundation soils already exist in place, these soils should be further tested and further evaluated such that a design can be promulgated. The pre-load method should be evaluated and a determination made if the pre-load will induce shear strength gain of the soft deposit and whether external drainage, such as wick drains, would be required. It is our opinion that the Observational Method requires a design be presented at the time of Permit application.	1			
2	Management Plan - page 8	Section 2.2.2.1 - Liner and Leakage Collection System Design	The HydroMet residue basin will consist of a double liner with an internal leakage collection system. Since this system is susceptible to rupture as a result of strains in the geomembrane or geosynthetic liner as a result of settlement or other localized conditions, we recommend that the pre-load/wick drain system be further evaluated and a design promulgated for review during the permit application process.	1			
3	Management Plan - page 33 and 34	Section 7.2.2	The management plan identifies that the HyroMet closure will include a 40 mil LLDPE membrane or a MPCA approved geomembrane and a geosynthetic clay liner (GCL) constructed over a working platform. As far as we know, the MPCA does not have an approved geomembrane list. They do have a guidance on their website. We recommend that the liner type be further investigated and the proposed liner be identified and detailed at the time of Permit application	1			

An alternative to conventional tailing management – "dry stack" filtered tailings

Michael P. Davies and Stephen Rice
AMEC Earth & Environmental, Vancouver, Canada

ABSTRACT: Development of large capacity vacuum and pressure belt filter technology presents the opportunity for storing tailings in a dewatered state, rather than as conventional slurry and/or in the "paste like" consistency associated with thickened tailings. Filtered tailings are dewatered to moisture contents that are no longer pumpable and need to be transported by conveyor or truck. Filtered tailings are placed, spread and compacted to form an unsaturated, dense and stable tailings stack (termed a "dry stack") requiring no dam for water or slurried tailings retention. This paper presents the basics of dry stack tailings management including design criteria and site selection considerations. Examples of several operations using dry stack technology are presented. Approximate operating costs for dry stack facilities are also included. Dry stack tailings are not a panacea for tailings management but present, under certain circumstances, an option to the tailings planner.

1 INTRODUCTION

Tailings management for the past several decades has largely involved the design, construction and stewardship of tailings impoundments. These impoundments are developed to store tailings slurry that typically arrives at the impoundment with solids contents of about 25% to 40%. The management of the traditional tailings impoundment is therefore a combination of maintenance of structural integrity and managing immense quantities of water.

The basic segregating slurry that has been used for conventional tailings management is only part of a continuum of products available to the modern tailings designer. Development of large capacity vacuum and pressure filter technology has presented the opportunity for storing tailings in a dewatered state, rather than as conventional slurry and/or in the "paste like" consistency associated with thickened tailings. Tailings are dewatered to moisture contents that are no longer pumpable. The filtered tailings are transported by conveyor or truck, and placed, spread and compacted to form an unsaturated, dense and stable tailings stack (a "dry stack") requiring no dam for retention. While the technology is currently (considerably) more expensive per tonne of tailings stored than conventional slurry systems, it has particular advantages in:

a) arid regions, where water conservation is an important issue
b) situations where economic recovery is enhanced by tailings filtration
c) where very high seismicity contraindicates some forms of conventional tailings impoundments
d) cold regions, where water handling is very difficult in winter

Moreover, "dry-stacks" have regulatory attraction, require a smaller footprint for tailings storage (much lower bulking factor), are easier to reclaim, and have much lower long-term liability in terms of structural integrity and potential environmental impact.

This paper will utilize the most common terminology in the industry. This includes:

- slurry tailings – the typically segregating mass of tailings that are in a fluidized state for transport by conventional distribution systems

- thickened tailings –partially dewatered but still a slurry that has a higher solids content by weight than the basic tailings slurry but is still pumpable. Chemical additives are often used to enhance slurry tailings thickening
- paste tailings – thickened tailings with some form of chemical additive (typically a hydrating agent such as Portland cement)
- wet cake tailings – a non-pumpable tailings material that is at, or near, saturation
- dry cake tailings – an unsaturated (e.g. not truly dry) tailings product that cannot be pumped.

The terms “dry stacked” or “dry stack” tailings have been adopted by many regulators and designers for filtered tailings. As long as the designers, owners and regulators understand that the tailings are not truly dry but have a moisture content several percent below saturation, there is nothing wrong with continuing the use of this terminology.

2 CONTINUUM OF TAILINGS

Figure 1 shows the continuum of water contents available for tailings management today and includes the standard industry nomenclature.

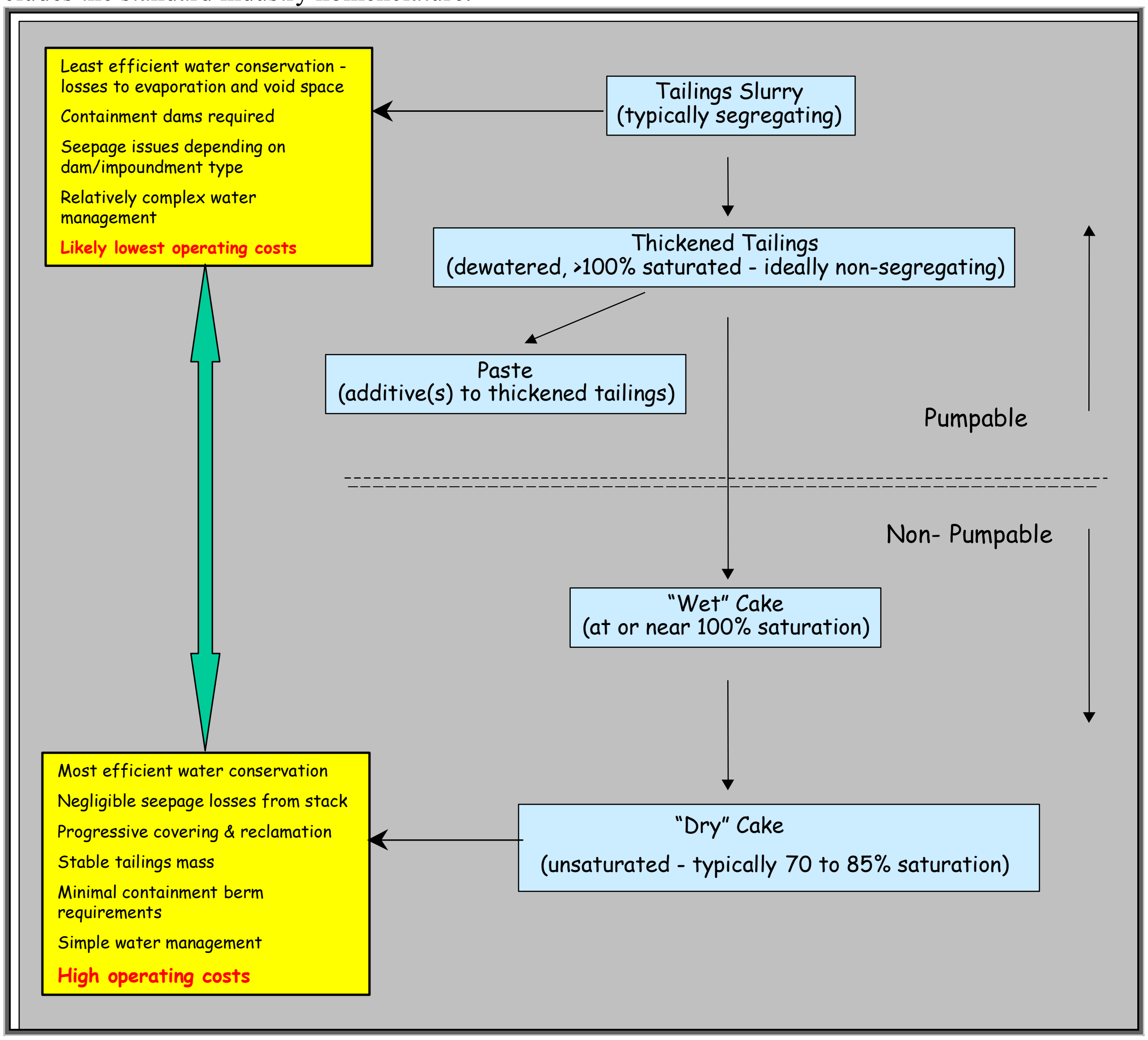

Figure 1. Tailings Continuum

Filtered tailings are typically taken to be the dry cake material shown in Figure 1. This material has enough moisture to allow the majority of pore spaces to be water filled but not so much as to preclude optimal compaction of the material.

Filtering can take place using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Figure 2 shows a typical filter press. Pressure filtration can be carried out on a much wider spectrum of materials though vacuum belt filtration is probably the most logical for larger scale operations.

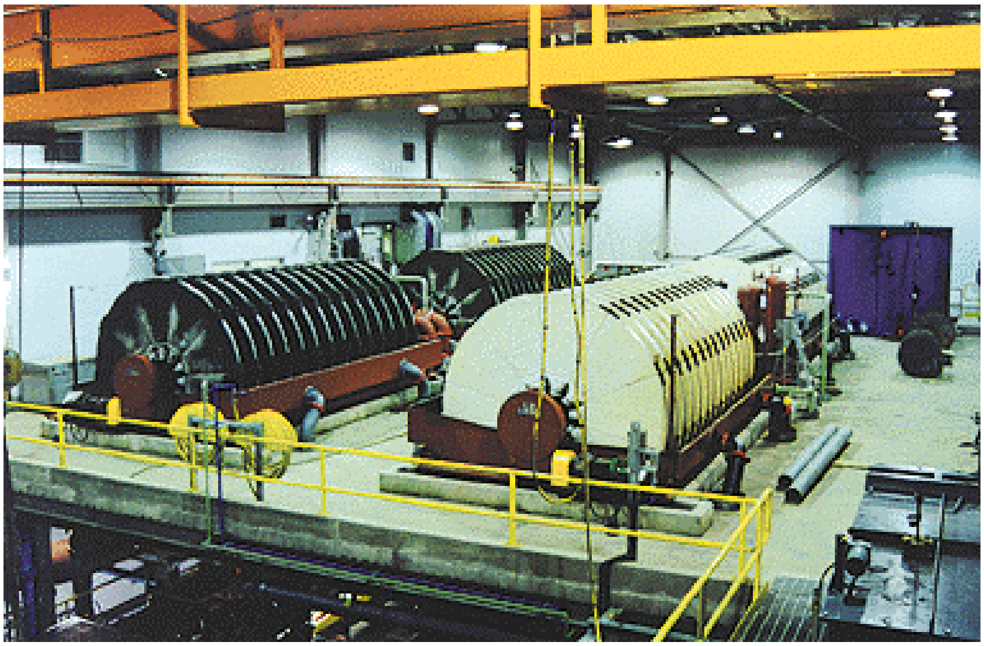

Figure 2. Example of a Filter Plant

The nature of the tailings material is important when considering filtration. Not only is the gradation of the tailings important, but the mineralogy is as well. In particular, high percentages of <74 µm clay minerals (i.e.. not just clay-sized but also with clay mineralogy) tend to contra-indicate effective filtration. Furthermore, substances such as residual bitumen (e.g. oil sands tailings) can create special difficulties for a filtration plant.

3 CONSIDERATIONS FOR FILTERED TAILINGS

As for any other form of tailings management, there are a number of issues that require careful consideration prior to selecting filtered tailings for a given project. Ultimately, these considerations are all about economics (capital, operating and closure liability) but require individual attention during the prefeasibility and feasibility stages of the project.

3.1 *General*

Whether filtered tailings are a candidate for a given project depends on the motivation to consider alternatives to a conventional slurried tailings impoundment. The motivation could include a more favourable, or timely, regulatory process or perhaps one of several technical issues presented by the site.

As noted in the introduction, filtered tailings could have application to meet technically challenging sites in:

a) arid regions

b) mines where dissolved metal recovery is enhanced by tailings filtration
c) high seismicity regions
d) cold regions
e) mine sites where space is limited as filtered tailings result in a lesser footprint than for slurried tailings.

In addition, site legacy issues are also part of the selection criteria as dry stacked tailings facilities are substantially easier to reclaim for mine closure, in most circumstances, when compared to conventional impoundments. Following is some elaboration on key issues to be considered.

3.2 *Water Management*

Where water is relatively scarce, either year round or seasonally due to extreme cold, sending immense quantities of water to quasi-permanent storage in the voids of a conventional impoundment can severely hamper project feasibility. By reclaiming the bulk of the process water in or near the mill, far more efficient recycle is achieved. Moreover, the amount of water "stored" in a dry stack facility will be typically >25% less than that in a conventional slurried impoundment even if 100% pond reclaim efficiency is achieved with the impoundment.

3.3 *Commodity Extraction*

Many mines, particularly those dealing with precious metals, can improve the bottom line by maximizing the amount of tailings water that can be reclaimed. Both the economic commodity (e.g. dissolved gold) and process chemicals (e.g. cyanide) can be recovered from the filtration water and one or more rinse cycles.

3.4 *Storage Availability*

Filtered tailings can be placed in a relatively dense state meaning that more solids per unit volume can be achieved. Furthermore, more aggressive use of available land (e.g. valley slopes) can be used with filtered tailings. As discussed in 3.5, lesser foundation conditions can also be considered in comparison to conventional impoundments.

3.5 *Geotechnical Issues*

The questionable manner in how some conventional impoundments are designed and/or operated provides support to considering the geotechnical advantages of filtered tailings. By objectively reviewing an instability database for conventional slurry tailings impoundments, over the past 30 years there have been approximately 2 to 5 "major" tailings dam failure incidents per year (Davies and Martin, 2000). There have been at least two events each year (1970-1999, inclusive). If one assumes a worldwide inventory of 3500 conventional tailings impoundments (a tenuous extrapolation at best), then 2 to 5 failures per year equates to an annual probability of between 1 in 700 to 1 in 1750. This rate of failure does not offer a favorable comparison with the 1 in 10,000 figure that appears representative for conventional water dams. The comparison is even more unfavorable if less "spectacular" tailings impoundment failures are considered. These impoundment failures, often equally economically damaging, are not just of older facilities constructed without formal designs, but include facilities designed and commissioned in the past 5 to 20 years - supposedly the "modern age" of tailings dam engineering.

The most common failure modes for slurry tailings impoundments are physical instability (including static and dynamic liquefaction) and water mismanagement issues (including lack of freeboard and seepage phenomena like piping). Filtered tailings placed in dry stacks are essentially immune to catastrophic geotechnical "failure" and can be readily designed to withstand static and seismic forces. A case can also be made for a reduction in the seismic design criteria based on failure consequence. This can significantly reduce operating costs. The unsaturated tailings mass is extremely resistant to saturation and seepage is governed by unsaturated hydraulic conductivities. Moreover, far less is required of foundation conditions as the unsaturated, largely dilatant tailings within a dry stack are not susceptible to static liquefaction or catastrophic breaching by an impounded pond should the foundation move creating substantive shear strains in the tailings mass.

3.6 *Reclamation/Closure Issues*

Dry stack facilities can be developed to consist of, or closely approximate, their desired closure configuration. Some form of assured surface runoff management plan is required. The tailings can be progressively reclaimed in many instances. In all cases, a closure cover material is required to resist runoff erosion, prevent dusting and to create an appropriate growth media for project reclamation.

The lack of a tailings pond, very low (if any) appreciable seepage from the unsaturated tailings mass and general high degree of structural integrity allows dry stacks to present the owner/operator with a comparably straight forward and predictable facility closure in comparison with most conventional impoundments.

3.7 *Environmental Stewardship*

Issues related to the environmental impacts from tailings dams were first seriously introduced in the 1970's in relation to uranium tailings. However, environmental issues related to mining have received attention for centuries. For example, public concerns about the effects of acid rock drainage (ARD) has existed for roughly 1,000 years in Norway. Today, environmental issues are growing in importance as attention has largely turned from mine economics and physical stability of tailings dam to their potential chemical effects and contaminant transport mechanisms. Recent physical failures such as Merriespruit, South Africa in 1994 and Omai, Guyana in 1995 and Los Frailes in Spain in 1998 illustrates this issue with most of the media reports highlighting the real or perceived environmental impacts of the failures.

Dry stacked tailings facilities have some tremendous potential environmental advantages over impounded slurried tailings largely because the catastrophic physical failures that define tailings management to non-supporters of the industry cannot occur. Moreover, leachate development is extremely limited due to the very low seepage rates possible. Oxidation processes are possible though the very slow rates for such, coupled with the limited seepage potential, limits or eliminates the concern of significant metallic drainage. Clearly, industry/regulatory standards of testing for potential operating and long-term impacts are essential. However, if the stack is operated to maintain its unsaturated character, any potential impacts should be predicted as acceptable except under unusual conditions.

Fugitive dusting, both during operation and upon closure, is a very real concern with dry stacks; particularly in arid environments. Progressive reclamation is the only effective method to address this concern.

3.8 *Regulatory Environment*

The regulatory environment worldwide is generally becoming less tolerant of one of humanities essential industries. Mining cannot exist without the creation of some form of tailings so the availability of a management strategy that is viewed (and correctly so) as both less invasive and less difficult to decommission as well as one that does not conjure up "massive" failure scenarios is a positive to the industry. As discussed elsewhere in this paper, the challenge is to get this regulatory friendly tailings management system to become cost-effective for those operations that would benefit (eg. in terms of the permitting process) from its consideration.

4 DESIGN CRITERIA

4.1 *General*

There are four main design criteria for filtered tailings:

1. filtering characteristics
2. geomechanical characteristics
3. tailings management
4. water management

In addition, the design must be compatible with an optimal closure condition (designing for closure). Implicit to the overall design criteria is project economics.

4.2 *Filtering Characteristics*

Determine the most cost-effective manner to obtain a dewatered product consistent with the other three design criteria (geomechanics, placement management and water management). Filter suppliers are both knowledgeable and helpful in this regard but some form of pilot test(s) is essential as every tailings product will exhibit its own unique filtering character. It is important to anticipate mineralogical and grind changes that could occur over the life of the project. The candidate filtering system(s) must be able to readily expand/contract with future changes at the mine with the least economical impact.

4.3 *Geomechanical Characteristics*

The strength, moisture retention and hydraulic conductivity characteristics of the tailings need to be established. The saturated tailings should be determined to "anchor" the results and tests as variable moisture contents are required to demonstrate the impact of the inevitable range of operating products. The other important geomechanical characteristic to determine is the moisture-density nature of the tailings. The unsaturated moisture-density relationship indicates in-situ density expectation as well as the sensitivity of the available degree of compaction for a given moisture content. From a compaction perspective, the filtered tailings should neither be too moist nor too dry. The optimal degree of saturation is usually between 60 and 80%.

4.4 *Tailings Management*

The design needs to be compatible with how the stack can be practically constructed using conventional haulage and placement equipment. Other than the capital and operating costs of the filtering process, the economics of dry stack management is the most important component of filtered tailings viability. Haul distance, placement strategy and compactive effort and additional works for closure and reclamation can make a larger incremental difference to the unit cost of a dry stack facility in comparison with a slurried impoundment.

The design should also clearly identify what contingency(s) will be in place if the filtering process experiences short-term disruptions. A temporary storage area or vessel is sound strategy. It is, however, the authors' experience that the filters should become part of the process plant under the management of the mill superintendent. The tailings processing then becomes integrated with the metal recovery functions and consequently down time is minimized because operation of the tailings system becomes critical to the overall mill performance.

4.5 *Water Management*

Surface water, particularly concentrated runoff, should not be permitted to be routed towards a dry stack. As important, the catchment and routing of precipitation (and any snow melt in colder climates) on the stack itself must be appropriately designed for. For the surface runoff within the overall catchment containing the dry stack, one (or more) of perimeter ditches, binds or under-stack flow through drains designed for an appropriate hydrological event(s) should be included in the design. For on stack water management, routing of flows to armoured channels and limiting slope lengths/gradients to keep erosion potential at a minimum are the best design criteria.

5 CONSTRUCTION AND OPERATIONAL CONSIDERATIONS

5.1 *General*

There are a number of construction and operational considerations that need to be accounted for in the design and planning of a dry stack. These considerations are very different from the construction and operational considerations normally associated with slurry tailings facilities. The main considerations are usually:

1. Site development
2. tailings transport and placement
3. water conservation and supply
4. reclamation and closure

In addition, there are often other considerations that need to be addressed on a site-specific basis for example co-disposal of waste rock in a combined mine waste management facility, storage of water treatment plant sludges etc.

5.2 *Site Development*

Site development for a dry stack normally consists of the construction of surface and groundwater control systems. There are normally two systems:

1. A collection and diversion system for non-contact water (i.e. natural surface water and groundwater from the surrounding catchment area that has not yet come into contact with the tailings). This system usually consists of ditches to divert surface runoff around the site and if necessary a groundwater cut-off and drainage system usually combined with surface water diversion. The cut-off system can range from simple ditches to sophisticated cut-off walls depending upon site conditions.
2. An interception and collection system for contact surface water, impacted groundwater, and seepage from the dry stack. This system usually consists of an underdrainage system of finger drains, toe drains, drainage blankets and french drains; collection sumps and ponds. Water collected in the ponds and sumps is usually used in process or pumped to a water treatment plant depending upon the site water balance. Liners for the facilities can also be components of the interception and collection system depending upon predicted impacts and regulatory requirements.

5.3 *Tailings Transport and Placement*

There are two methods in common use for transport of the filtered tailings to the tailings storage facility. These are conveyors or trucks and the equipment selection is a function of cost. Placement in the facility can be by a conveyor radial stacker system or trucks depending upon the application and the design criteria. Conveyor transport of tailings to the disposal site can be combined with placement by truck, so conveyor transport does not automatically result in placement by radial stacker.

The main issue associated with the placement of the filtered tailings by truck is usually trafficability. The filtered tailings are generally produced at or slightly above the optimum moisture content for compaction as determined in laboratory compaction tests (Proctor Tests). This means that a construction/operating plan is required to avoid trafficability problems. This is especially true in wetter environments since trafficability drops as moisture content rises and if the tailings surface is not managed effectively it can quickly become un-trafficable resulting in significant placement problems and increased operating costs. In addition, in high seismic areas there is often a design requirement to compact the tailings to a higher density in at least the perimeter "structural" component of the facility. This requirement increases the need for construction quality control. It is the authors' experience that the degree of compaction required for assured and efficient trafficability is often higher than the compaction required to achieve design densities.

Dry stack designs often incorporate placement zones for "summer/good weather" placement (dry, non-freezing conditions) and "winter/bad weather" placement (wet, or freezing conditions) with summer placement being focused on the structural zones. Again, this is especially true for facilities planned for wetter or colder climates were seasonal fluctuations are significant and predictable.

The key is to consider the environment and the design criteria and develop a flexible operating plan to achieve them.

5.4 *Water Conservation*

Often one of the main reasons to select dry stacked filtered tailings as a management option is the recovery of water for process water supply. This is particularly important in arid environments were water is an extremely valuable resource and the water supply is regulated (e.g. Northern Chile and Mexico). Filtering the tailings removes the most water from the tailings for recycle when compared with other tailings technologies as discussed earlier. This recovery of water has a cost benefit to the project, which offsets the capital and operating cost of the tailings system. It should be noted, that water surcharge storage needs to be factored in to the design of a filtered tailings system. Depending upon the application this can be a small water supply reservoir or tank.

5.5 *Reclamation and Closure*

One of the main advantages of dry stack tailings is the ease of progressive reclamation and closure of the facility. The facility can often be developed to start reclamation very early in the project life cycle. This can have many advantages in the control of fugitive dust, in the use of reclamation materials as they become available, and in the short and long term environmental impacts of the project. Progressive reclamation often includes the construction of at least temporary covers and re-vegetation of the tailings slopes and surface as part of the annual operating cycle.

6 ECONOMICS

6.1 *General*

It is hard to compare the economics of dry stack filtered tailings with other tailings options particularly conventional slurry tailings. This is mainly because of the difficulty of estimating the cost of closure and the potential costs associated with the long-term risk environmental liability associated with mine waste facilities. Therefore, the following discussion on economics is very subjective with a focus on perception.

6.2 *Capital Cost*

The capital costs are clearly a function of the size of the operation. Dry stack, filtered tailings currently appears to be limited to operations of 15000 tpd or less depending upon financial credits e.g. water recovery for use in process. Capital costs normally shift from the construction of engineered tailings containment structures to the dewatering (filter) plant. The capital costs may be further mitigated if the application is considered for small tonnage (less than say 4000 tpd) where the mine plan calls for paste backfill underground. Paste backfill requires a tailings processing plant with dewatering so incremental dewatering to produce filtered tailings make the economics more attractive. The capital cost appears to be much more attractive for operations under approximately 2000 tpd.

Other costs that should be factored into the equation are reduced costs associated with the smaller footprint, site development costs, and regulatory acceptance associated with dry stack tailings. These costs are often difficult to estimate accurately.

6.3 *Operating Cost*

The operating costs associated with the transport and placement of dry stack, filtered tailings are higher when compared with conventional slurry tailings, transported hydraulically and deposited in a tailings pond. The operating costs for a dry stack are difficult to summarize as every operation accounts for the costs differently. For example, if a mine uses a surface crew who do both tailings stack development as well as other duties, the cost/tonne will be much lower than a dedicated dry stack work force. Under the range of conditions for the presently operating dry stacks, the cost per tonne ranges from $1 to $10 but the average is more like $1.50 to $3. All costs are $US and include filtering, transport, placement and compaction in the facility.

6.4 *Reclamation and Closure*

Reclamation and closure costs are significantly reduced for dry stack tailings when compared with conventional tailings. This cost reduction is due to a reduced footprint and constructability. Other issues that need to be somehow factored into the “cost” of closure are the reduction in long-term risk and liability associated with dry stacks.

7 EXAMPLES

There are a growing number of dry stack facilities. At the same time, it would be fair to say that there is likely not any one of those operations who can point to an overall operating economic advantage to the practice. However, for at least three of the operating dry stack projects, the increased operating cost was sufficiently negated by other factors including regulatory issues and closure/liability costs.

The majority of the dry stacks are either in colder climates (e.g. Greens Creek, Alaska, Raglan, Quebec) or in arid environments (e.g. La Coipa, Chile). The La Coipa facility, developing at more than 15,000 tons/day, is one of the largest operating dry stacks. The La Coipa facility is located in a high seismic region with designed, and confirmed, structural integrity. Figure 3 shows the La Coipa facility a few years ago.

Figure 3. Dry-Stack Tailings Facility - Chile

8 SUMMARY AND CONCLUSIONS

There are several candidate scenarios where dewatered tailings systems would be of advantage to the mining operation. However, dewatered tailings systems may have less application for larger operations for which tailings ponds must serve dual roles as water storage reservoirs, particularly where water balances must be managed to store annual snowmelt runoff to provide water for year round operation.

Filtered tailings, a form of dewatered tailings, are not a panacea for the mining industry for its management of tailings materials. Purely economic considerations rarely indicate a preference for dry stacked tailings facilities over conventional slurry impoundments. However, under a growing number of site and regulatory conditions, filtered tailings offer a real alternative for tailings management that is consistent with the expectations of the mining industry, its regulators and the public in general.

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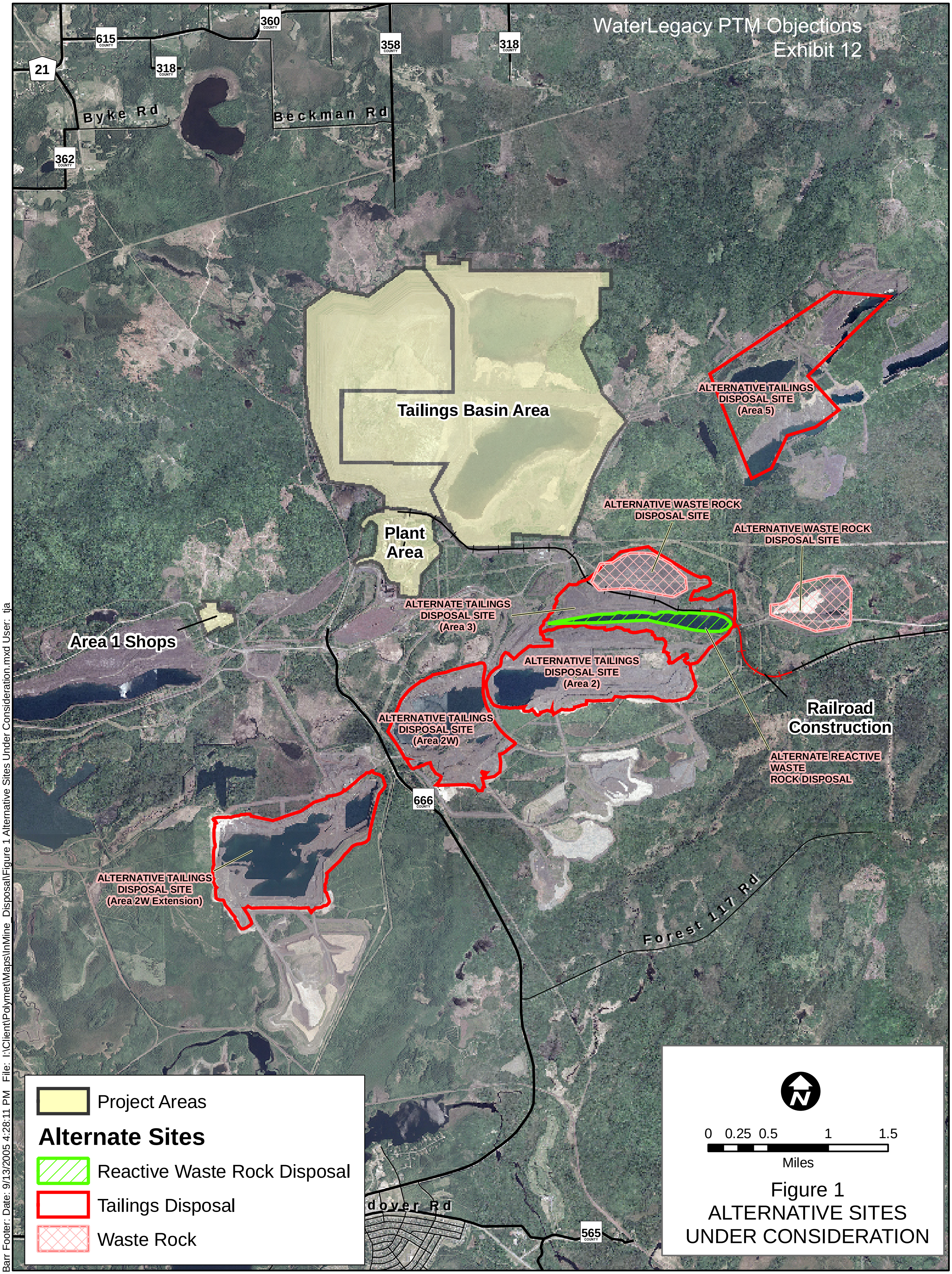

Figure 1
ALTERNATIVE SITES
UNDER CONSIDERATION

Barr Footer: Date: 9/13/2005 4:28:11 PM File: I:\Client\Polymet\Maps\InMine_Disposal\Figure 1 Alternative Sites Under Consideration.mxd User: tja

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Filtered Dry Stacked Tailings – The Fundamentals

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Abstract

Filtered tailings are becoming an increasingly common consideration for tailings management at many mines. There are more filtered dry stack tailings storage facilities than there are surface paste facilities yet the amount of guidance documentation on filtered tailings is virtually non-existent in compare to those same paste tailings facilities. The reason for this lack of guidance materials is uncertain but it has led to some unfortunate tailings management decisions based on misinformation about dry stacked tailings facilities in general.

This paper provides practical guidelines for the design and development of filtered dry stack tailings facilities. These guidelines are based upon the successful conceptualization, design, and operating experience at a number of these facilities. Issues related to target moisture content, appropriate testing methods and criterion, geotechnical conditions and placement considerations are included. The guidelines include specific reference to "lessons learned" from existing operations that will benefit designers and owners alike.

Filtration – End Member of the Tailings Continuum

The vast majority of the world's tailings facilities involve tailings impoundments. These impoundments are developed to store tailings slurry that typically arrives at the impoundment at solids contents of about 25% to 60% depending upon whether any thickening is carried out prior to deposition. These impoundments require construction and maintenance of structural integrity for the retention structures as well as management for what are typically immense quantities of water. Following operating these complex entities, closure of these impoundments can represent significant challenges in terms of both physiochemical reclamation as well as geotechnical considerations.

As the future of mining includes increasing scrutiny on the industry's stewardship of the natural environment, including use of water in most regions in the world, a commitment to alternatives beyond impoundments is often sought. The amount of water that is "lost" to the voids in the stored tailings, seeps or evaporates from the tailings impoundments is something being increasingly viewed by critical regulatory and public eyes that insist on evaluating whether there are viable alternatives for any given proposed mining development. This pressure to seek alternative tailings management approaches exists today and the future will likely only see these pressures intensified.

Conventional tailings impoundments remain the best alternative for the majority of operating and proposed mines around the world. These facilities are developed using tailings slurries that are the end waste product of the milling process. However, with advances in dewatering technologies over the past few decades, that tailings slurry is actually being only part of a continuum of tailings "states" available to the modern tailings designer. Development of large capacity vacuum and pressure filter technology has presented the opportunity for storing tailings in an unsaturated state, rather than as conventional slurry and/or in the "paste like" consistency associated with thickened tailings. For the minority set of projects that can find a non-slurried tailings alternative advantageous to optimal permitting and/or operating conditions, filtered tailings are often an excellent alternative.

Figure 1 shows the continuum of water contents available for tailings management and includes the standard industry nomenclature. With decreasing water content comes increased expense at hauling the tailings (e.g. pumping costs increase and then, upon becoming a wet cake, the tailing are no longer pumpable and other transport methods are required). However, as the water content decreases, which means increased water recovery within the process, the tailings are far more readily able to be used in self-supporting structural situations such as stacks.

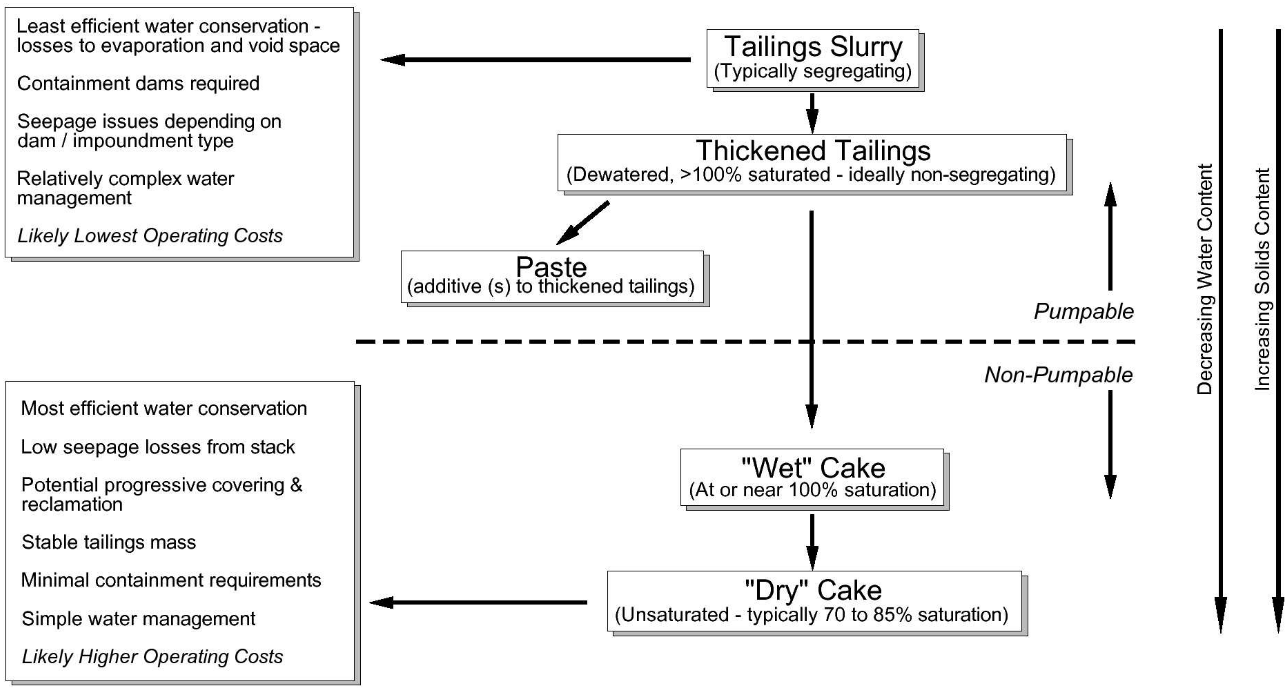

Figure 1: Tailings Continuum

Filtered tailings are typically taken to be the dry cake material shown in Figure 1. This material has enough moisture to allow the majority of pore spaces to be water filled but not so much as to preclude optimal compaction of the material.

Filtering and Dry Stacking

The Basics

Filtering of tailings can take place using pressure or vacuum force. Drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Pressure filtration can be carried out on a much wider spectrum of materials though vacuum belt filtration is probably the most logical for larger scale operations.

The nature of the tailings material is important when considering filtration. Not only is the gradation of the tailings important, but the mineralogy is as well. In particular, high percentages of <74 µm clay minerals (i.e. not just clay-sized but also with clay mineralogy) tend to contraindicate effective filtration. Furthermore, substances such as residual bitumen (e.g. oil sands tailings) can create special difficulties for a filtration plant.

Determining the most cost-effective manner to obtain a filtered product consistent with the geomechanical requirements of the tailings can be a challenge. Filter suppliers are both knowledgeable and helpful in this regard but some form of pilot test(s) is essential as every tailings product will exhibit its own unique filtering behaviour. It is important to anticipate mineralogical and grind changes that could occur over the life of the project. The candidate filtering system(s) must be able to readily expand/contract with future changes at the mine with the least economical impact.

Filtered tailings emerge from the process facility within a prescribed range of moisture contents discussed later. The tailings are then transported by conveyor or truck and then placed, spread and compacted to form an unsaturated, dense and stable tailings “stack” (often termed a "dry stack") requiring no dam for retention with no associated tailings pond. The filtered tailings are not “dry” but are unsaturated so the early nomenclature referring to them as dry is incorrect. However, it is doubtful this mislabeling has led to any misunderstandings amongst experienced designers, operators and regulators.

Each project needs to assess the potential applicability for filtered tailings based upon technical, economical and regulatory constraints. Experience shows the most applicable projects are those that have one or more of the following attributes:

1. Reside in arid regions, where water conservation is crucial (e.g. Western Australia, Southwest United States, much of Africa, many regions of South America, arctic regions of Canada and Russia)
2. Have flow sheets where economic recovery (commodity or process agent(s)) is enhanced by tailings filtration
3. Reside in areas where very high seismicity contraindicates some forms of conventional tailings impoundments
4. Reside in cold regions, where water handling is very difficult in winter
5. Have topographic considerations that exclude conventional dam construction and/or viable storage to dam material volume ratios
6. The operating and/or closure liability of a conventional tailings impoundment are in excess of the incremental increase to develop a dry stack.

To date, the two most common reasons to select dry stacked filtered tailings as a management option have been to recover water for process water supply and where terrain/foundation conditions contraindicate conventional impoundments. The recovery of water is particularly important in arid environments were water is an extremely valuable resource and the water supply is regulated (e.g. Chile, Western Australia, and Mexico). This recovery of water has a cost benefit to the project, which offsets the capital and operating cost of the tailings system. It should be noted that water surcharge storage needs to be factored in to the design of a filtered tailings system. Depending upon the application this can be a small water supply reservoir or tank. Where water is relatively scarce, either year round or seasonally due to extreme cold, sending immense quantities of water to quasi-permanent storage in the voids of a conventional impoundment can severely hamper project feasibility. By reclaiming the bulk of the process water in or near the mill, far more efficient recycle is achieved. Moreover, the amount of water “stored” in a dry stack facility will be typically >25 to 50% less than that in a conventional slurried impoundment even if 100% pond reclaim efficiency is achieved with the impoundment.

One of the main advantages of dry stack tailings over other tailings management options is the ease of progressive reclamation and closure of the facility. The facility can often be developed to start reclamation very early in the project life cycle. This can have many advantages in the control of fugitive dust, in the use of reclamation materials as they become available, and in the short and long term environmental impacts of the project. Progressive reclamation often includes the construction of at least temporary covers and re-vegetation of the tailings slopes and surface as part of the annual operating cycle.

How Common is Dry Stacking?

On a global basis, conventional tailings facilities (e.g. slurry tailings direct from mill into a tailings impoundment) make up by far the majority all existing tailings facilities. In terms of dewatered tailings, meaning those that are “lower” on Figure 1 than slurried tailings, there are a similar number of thickened/surface paste tailings facilities to filtered tailings facilities in terms of number of worldwide operations. There is, however, an intriguing dichotomy between available information about paste/thickened tailings and filtered tailings.

For paste/thickened tailings there has been a steady stream of publications (far outnumbering actual projects where the methods have been applied) and even annual specialty conferences. For example, each year since the late 1990s, there is an international conference on paste and thickened tailings where the presentations focus has necessarily been on potential advances and such more than actual case studies simply as there have not been sufficient projects to write about. Including the papers from these annual, and other, conferences, there are more than 200 publications on paste/thickened tailings including several guidebooks.

Filtered tailings, on the other hand, have simply not had the attention other dewatered tailings have had yet, as noted above, there are a similar number of actual operating mines using filtered tailings in comparison to, for example, thickened/paste tailings surface storage. There are but a handful of publications on filtered tailings/dry stacks and rare mention in conference proceedings. This is a curious development when the comparative number of actual projects using the various methods of tailings management is considered.

Figure 2, taken from a recent evaluation of global trends in dewatered tailings practice (Davies et al, 2010) provides a summary of the relative number of dewatered facilities on a global scale.

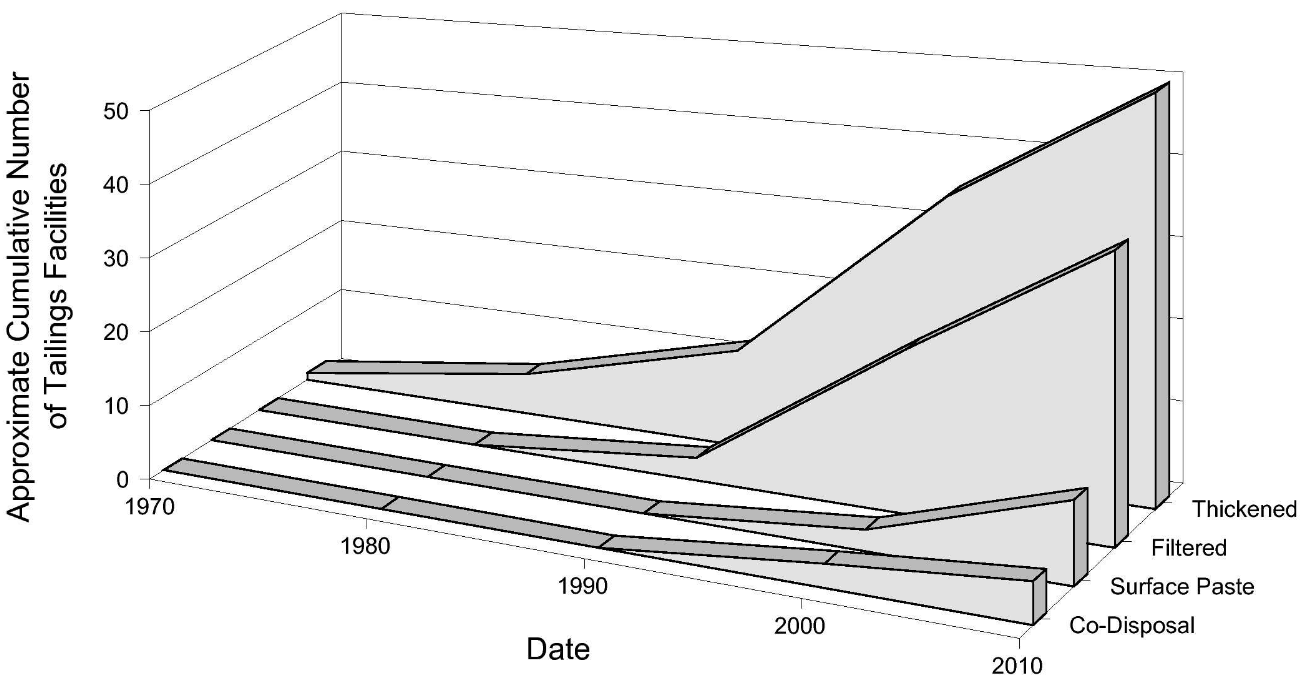

Figure 2: Trends in Use of Dewatered Tailings in Mining (after Davies et al, 2010)

Filtered Tailings - Design Guidelines

Overview

The strength, moisture retention and hydraulic conductivity characteristics of the tailings need to be established for any given project considering the technology. The strength and hydraulic parameters from saturated tailings should be determined to "anchor" the results and tests as variable moisture contents are required to demonstrate the impact of the inevitable range of operating products. The other important geomechanical characteristic to determine is the moisture-density nature of the tailings. The unsaturated moisture-density relationship indicates in-situ density expectation as well as the sensitivity of the available degree of compaction for any given moisture content. From a compaction perspective, the filtered tailings should neither be too moist nor too dry. The optimal degree of saturation is usually between 60 and 80%.

Filtered tailings can be placed in a relatively dense state meaning that more solids per unit volume can be achieved. Furthermore, more aggressive use of available land (e.g. valley slopes) can be used with filtered tailings. Lesser foundation conditions can also be considered in comparison to conventional impoundments.

Siting Considerations

While a filtered tailings dry stack will still require a foundation consistent with acceptable deformation criteria provided the loading conditions that the stack would be projected to be subjected to, static and dynamic, the range of topographic settings and foundation conditions where dry stacking will work is substantially wider than for conventional tailings impoundments. Avoidance of concentrated runoff water flows directed at the stack is one essential siting consideration. Other key siting considerations include:

- Placing the stack to avoid fugitive dusting from prevailing winds
- Avoiding placing where "blinding" off groundwater discharge areas (unless a sufficiently robust underdrainage system is designed, constructed and maintained)
- Optimizing the haulage and/or conveyance from the filtration plant; the tailings are no longer a slurry and a common "error" with those not familiar is dry stacks is to site the facility in same way one would a conventional slurry impoundment
- Potential ability to co-dispose with and/or abut waste rock dumps.

Tailings Testwork

The testwork required to provide sufficiently detailed engineering decisions at all project stages is relatively modest with filtered tailings. Minimum testing requirements are provided based upon project stage as follows:

Conceptual – Prefeasibility Project Stage(s)

- Approximate tailings gradation and mineralogy
- Flask or similar filtrate testing
- Standard Proctor (moisture-density)
- Vendor engagement – filtration and transportation

Feasibility Stage

- Tempe Cell laboratory testing
- Geochemical testwork
- Bench scale filtration testing
- Extended moisture density work
- Transport behavior evaluation

Detailed Engineering Stage

- Variable moisture testwork
- Possible field compaction trial

More detailed strength testing (e.g. triaxial) is an option and is only typically required for the largest of stacks as the range of strength parameters for the majority of tailings is within the margin of accuracy of the stability estimation programs used by designers. Strength testing that includes an ability to obtain key deformation moduli for the tailing is important, at the feasibility level, where deformation of the facility will govern performance (due, for example, to a weaker foundation scenario). Again, such considerations are only typically of relevance for the larger dry stacks being considered.

Target Moistures

Likely one of the most misunderstood design parameters for any filtered dry stack is the target moisture content for the filtrate. The degree of dewatering readily achievable depends upon the filtering technology adopted, the application rate of tailings into that technology and the tailings physical characteristics. However, what should be the more driving discriminator is what is required to develop the stack itself in a manner that expedites construction, maintains structural integrity post-compaction and provides all of the water management advantages that an appropriately developed dry stack exhibits.

From experience of developing more than ten dry stacks and testwork on many more, a very useful rule of thumb is to have the target moisture content be equivalent to the tailings Standard Proctor optimum moisture content as described by ASTM D-698 (ASTM 2011). While this target can vary as much as 1 or 2% under (wetter climates) to 1% over (extremely dry climates), the target has worked extremely well on all facilities presently existing that include those up to, and including, throughputs to 20,000 tpd. As filtered dry stacks increase in size, and appropriately the size of compaction equipment, it is probably that target moistures more consistent with the Modified Proctor may become more appropriate.

Facility Zonation

One of the most consistent “challenges” that operators of filtered dry stacks have is that no ore body is entirely consistent let alone the mechanical and human variability elements involved in transporting and placing/compacting those tailings. As a result, the filtrate’s character will vary and occasionally not meet the target moisture contents. Moreover, there can be extreme cold seasons in a year and/or infrequent but intense rainfall/snow events throughout a year that can all impact abilities to achieve consistent compaction of the filtered tailings.

The best solution for addressing filtrate and climatic variation is to design and operate the dry stack with “zones”. The facility can have, for example, a “shell” that is reserved for only filtrate that meets all specifications and is placed in optimal conditions during a day/week/year. The shell can then surround an interior of tailings that are provided the same/similar compactive effort but there is, and appropriately so, less expectation of these materials in global stability and otherwise evaluations.

Zonation can also exist for placement of waste rock within the dry stack. There are not fewer than five operating dry stacks that are provide encapsulation of mineralized waste rock that is provided the excellent oxygen barrier than a considerable thickness of unsaturated compacted tailings provides.

Water Management

Surface water, particularly concentrated runoff, should not be permitted to be routed towards a dry stack. As important, the catchment and routing of precipitation (and any snow melt in colder climates) on the stack itself must be appropriately designed for. For the surface runoff within the overall catchment containing the dry stack, one (or more) of perimeter ditches, binds or under-stack flow through drains designed for an appropriate hydrological event(s) should be included in the design. For on stack water management, routing of flows to armored channels and limiting slope lengths/gradients to keep erosion potential at a minimum are the best design criteria.

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1. A collection and diversion system for non-contact water (i.e. natural surface water and groundwater from the surrounding catchment area that has not yet come into contact with the tailings). This system usually consists of ditches to divert surface runoff around the site and if necessary a groundwater cut-off and drainage system usually combined with surface water diversion. The cut-off system can range from simple ditches to sophisticated cut-off walls depending upon site conditions.
2. An interception and collection system for contact surface water, impacted groundwater, and seepage from the dry stack. This system usually consists of an under-drainage system of finger drains, toe drains, drainage blankets and French drains; collection sumps and ponds. Water collected in the ponds and sumps is usually used in process or pumped to a water treatment plant depending upon the site water balance. Liners for the facilities can also be components of the interception and collection system depending upon predicted impacts and regulatory requirements.

Finally, the subject of facility lining is a prevalent topic and bound to arise on most every project where tailings are involved whether dry stacked or not. There is no hard set rule for lining versus no lining as, for the most part, lining with an appropriately designed and operated dry stack is more for political purposes than technical ones. Well-compacted filtered tailings at/near “optimum” moisture will have an equivalent hydraulic conductivity in a similar range to a typical liner element with average installation and other defects. The moisture content specified for optimal compaction is often very similar to the residual moisture content for the material and “drain down” is both slow and very limited in actual quantity of flow in most cases.

Tailings Transport/Placement

The design of any tailings dry stack needs to be compatible with how the stack can be practically constructed using the selected haulage and placement equipment. Haul distance, placement strategy and compactive effort and additional works for closure and reclamation make a larger incremental difference to the unit cost of a dry stack facility.

There are two methods in common use for transport of the filtered tailings to the tailings storage facility. These are conveyors or trucks and the equipment selection is a function of cost. Placement in the facility can be by a conveyor radial stacker system or trucks depending upon the application and the design criteria. Conveyor transport of tailings to the disposal site can be combined with placement by truck, so conveyor transport does not automatically result in placement by radial stacker.

The main issue associated with the placement of the filtered tailings by truck is usually trafficability. The filtered tailings are generally produced at or slightly above the optimum moisture content for compaction. This means that a construction/operating plan is required to avoid trafficability problems. This is especially true in wetter environments since trafficability drops as moisture content rises and if the tailings surface is not managed effectively it can quickly become un-trafficable resulting in significant placement problems and increased operating costs. In addition, in high seismic areas there is often a design requirement to compact the tailings to a higher density in at least the perimeter "structural" component of the facility. This requirement increases the need for construction quality control. It is the authors' experience that the degree of compaction required for assured and efficient trafficability is often higher than the compaction required to achieve design densities to meet geotechnical considerations.

Reclamation/Closure

Dry stack facilities can be developed to consist of, or closely approximate, their desired closure configuration. There is negligible facility deformation post-placement versus the considerable consolidation settlement conventional tailings undergo over what can be a very long period. Commensurately, the tailings can be progressively reclaimed in many instances.

The most important closure element is an assured surface runoff management plan with redundancy. In all cases, a closure cover material is required to resist runoff erosion, prevent dusting and to create an appropriate growth media for project reclamation.

The lack of a tailings pond, very low (if any) appreciable seepage from the unsaturated tailings mass and general high degree of structural integrity allows dry stacks to present the owner/operator with a comparably straight forward and predictable facility closure in comparison with most conventional impoundments.

Key Lessons Learned from Operating Dry Stacks

From design, operating and review knowledge of a majority of the world's dry stack tailings facilities, there are a number of "lessons learned" that should assist in any new facility being considered and/or in optimizing an existing facility. There are presented in no particular order of importance:

- Zonation is essential to a pragmatic and efficient tailings dry stack. Having an ability to deal with slightly off-specification material and/or still place in any weather condition removes many of the constraints that some have placed on dry stack development. It would be an extremely rare/unique situation that would not benefit and/or allow for a zoned approach to managing a given dry stack. Davies and Veillette (2007) describe the zonation approach adopted for the Pogo Mine in Alaska.
- If there is proper compaction and maintenance of target moisture contents, seepage is negligible. Instead of creating a complex system to capture seepage that will likely never appear, spend those resources more appropriately on surface water management measures that include a collection pond downgradient of the dry stack.
- Resaturation of properly placed and compacted filtered tailings is extremely difficult and not the concern many presume.

- Diversion ditches should be appropriately lined and the water routed in such a way that erosion of the tailings surface is not permitted to occur.
- Compaction specifications can be achieved in sub-freezing conditions if tailings windrows are compacted within a few hours of being transported from the plant.
- Heated bed liners are essential in colder climates.
- Tarps are excellent, though not elegant, way to provide short-term erosion protection in areas of intense rainfall where tailings windrows cannot be compacted prior to such rainfall events occurring (e.g. where they are daily events).
- Carrying on from the point above, dry stacks can be effectively developed in very wet conditions.
- Fugitive dust generation can be considerable in colder months (in cold climates) due to freeze drying of surface of the tailings stack.
- Filtration plants have occasional challenges and a temporary storage area(s) for one to three days of storage of material unsuitable for the dry stack is of great value to provide operational flexibility. This storage area should be close to the filtration plant so that the material can be readily reintroduced to the filtration process for permanent storage in the dry stack. In the case of lower tonnage operations, this storage can be achieved in large vessels/tanks whereas for larger operations, a lined impoundment is usually required.

Finally, filtered tailings dry stacks are not a panacea for mine waste management. They should be appropriately viewed as an alternative form of tailings placement and a part of the overall tailings continuum of options for today's designer/operator. There are site conditions, including regulatory regime, that make a tailings dry stack the best choice for certain projects. Where that is the case, the guidelines offered in this paper should provide a sufficient point to avoid the pitfalls that earlier dry stacks met and attain the successes that many current dry stacks demonstrate.

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memorandum

Project Name	PolyMet Dam Safety Permit Application Review	**Date**	05/15/17
To / Contact info	Jason Boyle (DNR)		
Cc / Contact info	Joe Henderson (DNR) and Mike Kunz (DNR)		
From / Contact info	Dick Van Zyl, Steve Gale (Gale Tec Engineering, Inc.), Cecilio Olivier (EOR) and Stuart Grubb (EOR)		
Regarding	Review Team Comments		

Background

PolyMet submitted two permit applications to the DNR for Dam Safety Permits for the NorthMet project. One application was for the Flotation Tailings Basin and the other was for the Hydrometallurgical Residue Facility (HRF).

To supplement the review process, the DNR requested that a team of top experts (EOR Review Team) be assembled to assess and comment on the proposed design, operation and maintenance of the facilities. The review approach focused on key elements similar to tailings basin review panels required by law in Montana and other western states. The review process included the following tasks:

- <u>Documents Review</u> – Including PolyMet's Dam Safety Permits applications, related technical documents, and comment tracking sheets.

- <u>Site Visit and Discussion</u> - Trip to Hoyt Lakes to develop observations and take field notes at the LTV/PolyMet tailings basin and proposed HRF sites. Meet with PolyMet and the tailings basin hydro designers to ask questions and discuss the different design elements.

- <u>Review Meetings</u> – Internal review meetings between EOR Review Team and DNR to discuss initial findings, need for additional information and develop final comments and recommendations. Meeting with PolyMet, DNR and the EOR Review Team to discuss final findings.

- <u>Draft and Final Report</u> - Present a Draft Report of findings to DNR and PolyMet. Prepare a Final Report including a response to comments on the Draft Report.

EOR Review Team

EOR assembled a Review Team of experienced experts in mining geotechnical engineering. The Review Team included:

- ***Dirk van Zyl, PhD, PE.*** Dirk is on the faculty of the University of British Columbia and consults with mining companies worldwide on tailings basin design. He was formerly on the faculty of the University of Nevada – Reno, and he has worked for several consulting companies. Dr. van Zyl has authored or co-authored over 120 papers on mining topics, including tailings basin management. He currently serves on several review panels in Montana and on the review panel that previously investigated the Mt. Polley dam failure.

- ***Steve Gale, PE**.* Steve is the President of Gale-Tec Engineering Inc. in Minneapolis, Minnesota. He has over 30 years of experience working as a geotechnical engineer. Mr. Gale and his company provide consulting services on all aspects of tailings basin design, management, and closure, including dam safety analysis and permitting. He has worked on many of the tailings basins on Minnesota's Iron Range.

Resumes are included in Attachment 1.

Review Process

The EOR Review Team went through the following documents:

- Technical Memorandum: NorthMet Geotechnical Data Package – Volume 1 (Flotation Tailings Basin) – Version 4 Modeling Outcomes Summary. Barr Engineering, April 2, 2013.
- NorthMet Dam Safety Permit Application: Flotation Tailings Basin. Barr Engineering, July, 2016.
- NorthMet Dam Safety Permit Application: Hydrometallurgical Residue Facility. Barr Engineering, July 2016.
- 2015 Tailings Basin Dam Safety Inspection Report. Barr Engineering, August 2016
- Technical Memorandum: DNR Review of PolyMet's Dam Safety Permit Application – Tailings Basin Comment 9 – LTVSMC Coarse Tailings Strength. Barr Engineering, December 30, 2016.
- Technical Memorandum: Tailings Basin Cell 2E North Dam – Modified Buttress as Alternative to Cement Deep Soil Mix Zone. Barr Engineering, December 30, 2016

The EOR Team (along with the DNR, PolyMet and Barr Engineering) conducted a site visit to the LTV tailings basin site and proposed HRF facility in September 29th, 2016. The EOR Review Team also met with PolyMet and Barr Engineering to discuss comments and questions on the proposed NorthMet project. A follow up meeting to discuss and review comments was held with the same participants at DNR headquarters on December 5th, 2016. The EOR Review Team and DNR met on several occasions to discuss the review's status .

Review Comments

The detailed EOR Review Team comments are presented in the review tables of Attachment 2. The columns on the tables include:

- *Comment/Concern* - These initial comments were written by the EOR Review Team, reviewed by DNR, and submitted to PolyMet in December, 2016.
- *PolyMet Response* - PolyMet provided these written and/or verbal responses to the initial comments.
- *Final Comments* - After considering PolyMet's response, the EOR Review Team prepared these comments contained in this column.
- *Recommendations* - The EOR Review Team recommends that the comments and issues be addressed as follows:
    - *Address Pre-Permit* - These issues will require additional information before a permit can be issued. This may require resubmittal of the complete permit application.

- *Address Post-Permit & Make Condition of Permit* - These issues require additional information, but they are not likely to have a bearing on the DNR's decision to grant or deny the permit. They may affect future construction and operation of the facilities. Some of these comments can only be addressed while the facilities are operating. PolyMet must address these comments if the permit is granted.
- *Address Pre-Construction* - These issues also require additional information, but they are not likely to have a bearing on the DNR's decision to grant or deny the permit. PolyMet must provide more information before beginning construction of the facility if the permit is granted.
- *Condition of Permit Recommendation* - The EOR Review Team provides elements and recommended language to be incorporated into the permit, either pre-permit or as a condition of the permit.

Comments on PolyMet's Design, Approach and Redevelopment of the LTV Tailings Basin

<u>Observational Method (Comments #1, #4, #5 and #7 in Attachment 2)</u>
The Observational Method is a well-documented and often-used approach to tailings dam construction and maintenance. The Observational Method steps are:

1) Predict behavior with detailed calculations,
2) Design with contingencies,
3) Construct with monitoring and
4) Compare measurements with predictions and redesign if necessary.

The EOR Review Team agrees that the Observational Method can and should be used during construction, but it is not a substitute for careful initial design. The EOR Team concluded that the permit application lacks the detail and description of contingencies for the Observational Method to be effective. If monitoring data indicate a potentially unsafe condition during construction, then the alternate construction methods and designs (contingencies) must be already in place so that they can be implemented immediately.

<u>Peat Layers and Slimes Layers (Comments #3, #4 and #7 in Attachment 2)</u>
The former LTV tailings basin was constructed over layers of peat in some areas. Layers of slimes (very fine-grained taconite tailings) were also included in the construction of the tailings basin dam. Both peat layers and slimes layers have very low shear strength, which could potentially contribute to a dam failure. The tailings basin can be designed to safely mitigate for these conditions, but the areas with peat and slimes must be well-defined and tested. The EOR Team commented that additional data should be gathered on the peat layers and slime layers, and that the design may need to be modified in the future in accordance with the Observational Method.

<u>Cement Deep Soil Mixing (CDSM) & Dam Toe Buttressing (Comments #2 and #11 in Attachment 2)</u>
In the permit application, PolyMet proposed constructing the dam with both CDSM and dam toe buttressing (reinforcement usually using waste rock). CDSM uses large-diameter drills to drill into the base of the tailings basin dam and mix Portland cement with the existing materials. Placing of these CDSM "pillars" close together in a line creates a kind of shear wall that increases the shear strength of the material. The construction needs to be carefully monitored in the subsurface to make

sure that the pillars are constructed as designed. CDSM is often used in the construction of embankments and dams, but to our knowledge has not been used in a tailings basin.

Dam toe buttressing places heavy materials at the toe of the tailings basin dam to prevent the toe of the dam from sliding and causing a dam failure. The required size and weight of the buttress increase as the height of the dam increases.

The EOR Review Team commented that additional monitoring would be required during CDSM construction and during operations and closure to assess the effectiveness of the CDSM. Since then, PolyMet has removed CDSM from the design plans in favor of using larger dam toe buttresses. The design plans with additional buttresses will have several advantages:

- The technology is better understood on tailings basin dams,
- Construction and maintenance are above ground, so critical observation and monitoring can be done with greater confidence, and
- The buttress can be constructed incrementally over an extended period of time, whereas the CDSM must be fully completed prior to placing the basin into service.

Peat deposits should be removed near the toe of the existing tailings basin dam so that the new buttress will have a solid footing. If peat deposits are not fully removed, the EOR Review Team commented that additional analysis should be required to evaluate the stability of the buttress toe that may be constructed over localized soft soils. PolyMet indicated that buttress construction will specify the complete removal of peat soils. The EOR Review Team also recommended performing additional analysis for other potential impacts due to additional wetland fill or the geochemistry of the buttress material.

Water Ponding (Comment #5 in Attachment 2)

As currently designed, a pond of water will be maintained on top of the tailings basin in perpetuity. During mining operations, the residue from the processing plant (tailings) is pumped to the pond as slurry, and water is returned to the plant after the tailings settle out. PolyMet developed stability analysis models that show the volume and location of the pond at various times during the operating life of the tailings basin. This stability analysis was based on maintaining a beach length of 625 feet between the inside crest of the dam and the edge of the water within the tailings basin. This would minimize the potential for the water to rise and cause erosion at the edge of the basin.

The EOR Review Team commented that some of the model runs did not seem to correctly account for a potential rise in water levels, the location of the beach around the pond, and the distance to the edge of the tailings basin. PolyMet indicated that the design included a 4 feet head increase while still keeping the water pond at a 625 feet distance from the crest of the perimeter dike. The EOR Review Team recommended that a water pocket distance of less than 625 feet (or in direct contact with the tailings dam) be analyzed as an event/condition of the Observational Method approach.

Existing Structures (Comment #6 in Attachment 2)

The EOR Review Team commented that some of the existing structures associated with the existing tailings basin had not been specifically addressed in the plan for future construction. The EOR Team recommended that the permit includes language that requires all existing structures to be investigated and properly abandoned before construction to ensure that dike stability is maintained.

Bentonite Addition (Comment #8 in Attachment 2)
To minimize water seepage from the tailings basin, bentonite will be added to the soils at the top of the basin during the closure and reclamation process. The permit application only lists alternatives for placing the bentonite that will be pilot tested and field tested later. The EOR Review Team commented on specific elements that should be included in the field testing that would impact the permeability of the bentonite amended tailings. Once the preferred bentonite application method is selected, the EOR Review Team recommended developing material and installation specifications and a detailed protocol for both a laboratory and a field pilot study.

Statistical Analyses (Comment #9 in Attachment 2)
Geotechnical tests were performed to determine the shear strength of the tailings at hundreds of locations around the existing tailings basin. Statistical analyses are used to calculate the overall strength and stability of the basin. EOR Review Team commented that some of the geotechnical test results (i.e. low coarse tailings friction angles) were excluded from the statistical analyses. Because of their importance in the overall stability of the basin, the EOR Review Team recommended that coarse tailings friction angles be considered as a variable condition in the Observational Method process. This would also provide a consistent and proper procedure for future analyses.

It should be noted that including all the geotechnical results in the statistical analyses did not significantly reduce the global factor of safety. Nevertheless, the EOR Review Team recommended using the Observational Method to enhance instrumentation and monitoring at those discrete cross sections where lower friction angles could occur. If lower friction angles are observed, the statistical analysis must be rerun to verify that this localized factor of safety is still acceptable.

Wet Closure vs. Dry Closure (Comment #10 in Attachment 2)
Wet closure of the tailings basin is currently proposed, meaning that the top of the tailings basin will have a permanent pool of water on top of the basin. Wet closure has ongoing costs like; maintaining water levels to prevent flooding and drying out, erosion repair, treatment of discharged water and on-going monitoring. Dry closure (no water ponding) requires a greater initial investment, but has much lower ongoing maintenance costs and less long-term environmental risk.

The EOR Review Team did not proposed dry closure as a permit requirement at this time. The EOR Review Team recommended that if the wet closure is permitted, the DNR should require PolyMet to continually review the current state-of-the-practice for dry closure techniques prior to starting any tailings basin closure activities.

General Discussion of Issues – HydroMet Residue Facility

Stability of Underlying Soils (Comment #1 and #2 in Attachment 2)
The soft ground beneath the proposed residue facility consists of up to 30 feet of slimes, peat and tailings concentrate. This will not be an adequate foundation for the 80 foot high basin. Three potential remediation alternatives have been considered:

- Pre-loading the existing material with 50 feet of rock and soil to compress and consolidate the underlying material. This is the method currently proposed by PolyMet.
- Installing wick drains that will allow water to flow out of the existing material, thereby increasing its shear strength.
- Removing the existing material and any soft soils before constructing the basin.

The basin will have a geomembrane or geosynthetic liner. The liner could deform and fail if the existing underlying material cannot support the material added to the basin.

The EOR Review Team commented that the proposed pre-load design should be re-evaluated to determine if it will adequately surcharge and compress the existing material.

<u>Geomembrane (Comment #3 in Attachment 2)</u>
The EOR Review Team commented that more information was required in the permit application to evaluate the geomembrane liner system. Barr Engineering provided the information, so this issue has been closed.

Attachment 1 - Resumes

Dirk van Zyl

Dirk Jacobus Albertus van Zyl

CURRICULUM VITA

EDUCATION:

Executive Master of Business Administration, 1998, University of Colorado

Ph.D., 1979, Purdue University

M.S., Civil Engineering, 1976, Purdue University

B.Sc. (Honors), Civil Engineering, 1974, University of Pretoria, South Africa

B.Sc., Civil Engineering, 1972, University of Pretoria, South Africa

EXPERIENCE:

January 2010 to Present: **Professor and Chair of Mining and the Environment, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC.**

January 2008 to December 2010: **Professor of Mine Life Cycle Management, Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver, BC.**

September 1999 to December 2007: **Professor of Mining Engineering and Director of the Mining Life-Cycle Center, Mackay School of Mines (changed to Mackay School of Earth Sciences and Engineering on January 1, 2004), University of Nevada, Reno. Chair of Department of Mining Engineering from 2002 to 2007.**

April 1999 to present: **Tailings and Mine Rock Management Consultant Reno, Nevada and Vancouver, BC**

September 2001 to August 2008: **Chairman of Mining Engineering, Mackay School of Earth Sciences and Engineering, College of Science, University of Nevada, Reno**

1998 – 1999 **TRC Companies Inc.** **Denver, Colorado**
Vice President Mining Industry

1992 - 1998 **Golder Associates Inc.** **Denver, Colorado**
Principal, Vice President Mining

1990 - 1991 **EIC, Corporation** **Denver, Colorado**
President and Principal Engineer

Dirk van Zyl

1988 - 1990	**Welsh Engineering, Inc.** *Vice President (also member Board of Directors)*	**Denver, Colorado**
1987 - 1988	**CH2M HILL** *Geotechnical Engineer*	**Denver, Colorado**
1984 - 1987	**Colorado State University** *Associate Professor, Civil Engineering Department, Geotechnical Engineering Program*	**Fort Collins, Colorado**
1982 - 1984	**University of Arizona** *Assistant Professor, Department of Civil Engineering and Engineering Mechanics*	**Tucson, Arizona**
1979 - 1982	**Steffen Robertson & Kirsten,** *Senior Geotechnical Engineer, Project Manager and Office Manager*	**Johannesburg, South Africa, Denver, Colorado, Tucson, Arizona**
1975 - 1979	**Purdue University**	**West Lafayette, Indiana**
1974 - 1975	**Steffen Robertson and Kirsten** *Geotechnical Engineer*	**Johannesburg, South Africa**
1973 - 1974	**National Institute for Transportation and Road Research, Council for Scientific and Industrial Research** *Assistant Research Officer*	**Pretoria, South Africa**

PROFESSIONAL AFFILIATIONS:

Registered Professional Civil Engineer – California, Indiana

Registered Professional Engineering – British Columbia

Member, Canadian Institute of Mining, Metallurgy and Petroleum

Member, Society of Mining, Metallurgy and Exploration

Dirk van Zyl

AWARDS AND HONORS:

J.E. Jennings Award from South African Institute of Civil Engineers, 1981, Best Geotechnical Paper Published in the World by South African Authors for "The Piezometric Probe - A Useful Investigation Tool", In Proceedings of 10th Int. Conf. on Soil Mechanics and Foundation Engineering, Stockholm, Sweden.

Robert Peele Memorial Award, Society of Mining Engineers of the American Institute of Mining Metallurgical and Petroleum Engineers, 1986, best paper by young member "Construction Investigation of a Clay Heap Leach Pad" In Gold and Silver Heap and Dump Leaching Practice.

Society for Mining Metallurgy and Exploration Inc., 1992, Mining and Exploration Division, Distinguished Service Award

Society for Mining Metallurgy and Exploration Inc., 1998, President's Citation:
For continuous and consistent support of the Society's technology transfer and education through the creation and presentation of timely and industry relevant short courses, and the writing of applied engineering publications.

Society for Mining Metallurgy and Exploration Inc., 2003, Distinguished Member Award

Bureau of Land Management, 2005, Sustainable Development Award, Citation:
The award recognizes Dr. van Zyl's contributions over the last five years to a better understanding of mining and its contributions to sustainable development.

Adrian Smith International Environmental Mining Award, 2006.

Distinguished Lecturer, Environment and Social Responsibility Society, CIM Council. Topic: *Tailings Risk Management*. 2016 to 2017.

SPECIAL ASSIGNMENTS:

Dirk van Zyl was a member of the Independent Expert Investigation and Review Panel (Dr. Norbert Morgenstern, Chair and Steven Vick) appointed by the British Columbia Government as well as the Williams Lake and Soda Creek Indian Bands to investigate the Mount Polley tailings failure in 2014. The Panel was appointed on August 18, 2014 and provided their report on January 30, 2015. Full details of the report, the background information and field and laboratory investigations are available at https://www.mountpolleyreviewpanel.ca

Member of Expert Panel on Tailings Management, International Council for Mining and Metals, 2016

Dirk van Zyl

TECHNICAL PAPERS:

Huallanca, W., Reyes, A., Parra, D. and van Zyl, D. (2015). Determination of a tailings storage facility capacity via finite-element and finite-strain methods, Tailings 2015, Santiago, Chile: Gecamin, 9pp

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Xavier, A., Veiga, M.M., van Zyl, D. (2014). Introduction and Assessment of a Socio-Economic Mine Closure Framework. Submitted to *The Extractive Industries and Society Journal.*

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Pitzer, C. and van Zyl, D. (2013). Resilience –The new risk management, Proc. 35th International Conference on Safety in Mines Research Institutes, London: Institute of Materials, Minerals and Mining, 10pp

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Fredlund, M., Zhang, J., van Zyl, D., and Wells, S. (2012). Multidimensional coupled sedimentation and consolidation theory, Tailings and Mine Waste 2012, Colorado State University, pp 313 – 324.

Wachtel, T. Quaranta, J.D., van Zyl, D. and Siriwardane, H. (2012). Seepage risk sensitivity for a potential failure mode analysis due to mining near bodies of water, Tailings and Mine Waste 2012, Colorado State University, pp 395 – 406.

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Fredlund, M., Thode, R. and van Zyl, D. (2011). Slope stability model of the Questa rock pile – phase 1, Tailings and Mine Waste 2011, Norman B. Keevil Institute of Mining Engineering, UBC, pp 467 – 478.

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Caldwell, J. and Van Zyl, D. (2011). Thirty years of tailings history from tailings and mine waste, Tailings and Mine Waste 2011, Norman B. Keevil Institute of Mining Engineering, UBC, pp 79 – 91.

Van Zyl, D. and Caldwell, J. (2011). Brief history of the conference series, Tailings and Mine Waste 2011, Norman B. Keevil Institute of Mining Engineering, UBC, pp 1 – 4.

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Zhou, J.W., Zhou, A.G., Van Zyl, D., Tang, Z.H. and Bu, J.W. (2011). Mine closure in China – problems, strategies and forecasts, In: Mine Closure 2011, Vol. 2, Fourie, A, Tibbett, M and Beersing, A (Eds.), Australian Centre for Geomechanics, pp 501-509.

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Conference on Cyanide and the Environment (1985), 2 volumes, Civil Engineering Dept., Colorado State University, Fort Collins, Colorado, 577 pp.

PROFESSIONAL PROFILE

EARTH AND TAILINGS DAMS

Stephan M. Gale

1995-Present President and Founder – Gale-Tec Engineering, Inc.
1976-1994 Project Engineer to Director of Engineering/Shareholder – STS Consultants, Ltd.

EDUCATION

M.S., Geotechnical Engineering, Ohio State University - 1976
B.S.C.E., Civil/Structural Engineering, Ohio State University – 1974

REGISTRATION

Professional Engineer: Minnesota, Illinois, Iowa, Wisconsin, Ohio and Nebraska

PROFESSIONAL ACTIVITIES

American Society of Civil Engineers
- 1973 - Present
- Elected Fellow in 1992 & Life Member in 2016
- Geotechnical Journal Reviewer

American Soc. of Testing and Materials
- 1995-Present
- Committee D-18-Soils
- Committee D-35-Geosynthetics

Engineers Club of Northern Minnesota
- 1985-Present

Society of Mining Engineers
- 1988-Present

University of Minnesota
- CE 4102 Capstone Design Mentor, 2003-2006

AWARDS/CERTIFICATIONS

Diplomate – Geotechnical Engineering by ASCE – GeoInstitute - 2013

Minnesota Senate and House Agricultural Committee Task Force, "Liquid Manure Storage in the Karst Region", 2000.

Young Engineer of the Year, American Society of Civil Engineers, 1988

Who's Who in Science and Engineering-Second Edition, 1993

EXPERIENCE

Mr. Gale has 40 years' experience in tailings, earth dam and embankment evaluation and design. He has been evaluating and designing tailings dams and preparing MDNR Dam Safety Submittals for over 30 years. He has presented lectures at conferences around the world ("Upstream Dam Construction: An Instrumented Test Fill Evaluation", presented in The Hague, Netherlands).

Dams and Levees

- Principal Engineer in-charge of construction and eventual closure of a 120-foot high, 4-mile perimeter Tailings Basin and Dike No. 1 for Eveleth Mines/United Taconite in Forbes, MN. Seepage and stability evaluations were required to be submitted to MnDNR over a 20 year period prior to closure in 1999. Work also included preparation of the closure/reclamation plan.

- Principal Geotechnical Engineer for Tailings Basin and Dike No. 2, also on the United Taconite property. Responsible for stability and seepage studies and the preparation of the yearly Dam Safety Report for the period 2000-Present.

- Principal Engineer in-charge of the design, including preparation of plans and specifications, for raises to the Hibbing Taconite Company Tailings Basin perimeter retention dam, including their Western Dam and Dams SD-2 and SD-3.

- Principal Geotechnical Engineer for the evaluation and preparation of the repair plans and specifications for 2-miles of a Mississippi River Flood Control Levee at Lock & Dam No. 3 in Welsh, MN. The work included evaluation of the existing earth levee and preparation of plans and specifications for reconstruction of the levee, repairing erosion and establishing riprap and dam bedding requirements.

- Mr. Gale, as a national geosynthetics expert, was retained by the U.S. Corps of Engineers in 2008 to assist them in the re-write of their Engineering Manual – "Engineering Use of Geotextiles" in Levees, UFC 3-220-08.

- Principal Geotechnical Engineer for the assessment of a large wetland complex and surrounding levees in Necedah, WI for the U.S. Fish & Wildlife Service. Mr. Gale participated in the design of a culvert to pass both fish and large flood flows and completed an evaluation and design for a roadway/levee protection system.

- Principal Geotechnical Engineer to evaluate and prepare repair plans and specifications for the Neill Lake Berm/Levee in Eden Prairie, MN. The project involved the inspection and evaluation of a 1000 ft long levee which maintained the water level in a recreational lake. Animal burrow holes, seepage and stability were assessed. Geophysical studies were performed to assess foundation conditions. Plans and Specifications was prepared for the repair.

- Principal Geotechnical Engineer for the field investigation and subsequent assessment of various berms/levees within the Kimmes-Tobin natural wildlife area for the Wisconsin DOT. The project involved the evaluation and repair design for levees that were subject to overflow, erosion and animal penetrations.

- Project Engineer for the evaluation of Golden Dam for the Arizona Water Commission. The dam was built to create a recreational lake, however, large amounts of under-seepage prevented water impoundment. Studies included seepage and under-seepage analyses, uplift analyses and reconstruction recommendations including downstream buttress fills and upstream blankets.

- Project Engineer evaluating two 80-ft high flood retention earth dams and spillways built during the 1930's in Ohio for the Corps of Engineers - Huntington District. Mr. Gale supervised the exploration program and then prepared the evaluation report for the Bolivar and Beach City Dams. Finite element seepage analyses, evaluation of relief wells and slope stability evaluations using both computer and hand solutions were carried out.
- Principal Engineer in-charge of the dam inspection and performance evaluation of a perimeter dam system containing the Whitewater Reservoir, in Aurora, Minnesota. The reservoir is a water resource that provides make-up water for a Minnesota Power plant and LTV Steel Mining Company's iron-ore processing plant. The studies included instrumentation monitoring and evaluation. The studies pointed out deficiencies in embankment stability and detailed necessary corrections.
- Mr. Gale was retained as an expert to review the distress and assist in the repair of The Earth City levee near St. Louis, MO during a 1993 flood event. The Earth City levee is a three mile levee protecting an industrial park from the Missouri River. When the Chesterfield levee burst in 1993, Mr. Gale was called in to examine and make critical observations to the adjacent Earth City levee which was on the verge of failing. The levee protected over $1B worth of property including the Whirlpool Corporation and the United Parcel Service Midwest distribution warehouses. Five (5) ft. high sand boils were occurring landward of the levee. Soon into the evaluation, it was identified that sixty foot deep relief wells were not providing pressure relief and repairs were ordered. The levee survived the flood!
- Mr. Gale was retained as an expert to analyze and review the collapse of a 22-foot low-profile steel-arch culvert pipe for Inland Steel Mining Company (now Arcelor Mittal) during development of their new Laurencian pit. The arch collapse was attributed to inability of the granular backfill to resist high arch corner pressures caused by 240-ton mine trucks operating over the arch that had been placed at a skew with an embankment fill.
- Principal Engineer responsible for the evaluation and design over a 15 year span of Hibbing Taconite Company projects involving their Tailings Basin in Hibbing, MN including sheet pile walls for spillway channels, for erosion protection systems for open water areas and for the failure investigation of two 96–inch diameter water intake structures that had collapsed.
- Mr. Gale was the investigator of downstream scour of a 1911 constructed Amburson type concrete dam on the Blue Earth River in Rapidan, MN. Mr. Gale initiated a rock boring investigation in order to provide an assessment of rock slope deterioration. Mr. Gale provided an assessment of the potential for undermining of the downstream apron and prepared a filter/riprap design.

A SAMPLING OF PUBLICATIONS

"Reliability of Settlement Prediction-Case History", ASCE – Journal of Geotechnical and Geoenvironmental Engineering, Vol. 137, Number 4, April, 2011

"Embankment on Sludge: Predicted and Observed Performances", Canadian Geotechnical Journal, 2007

"Upstream Dam Construction: An Instrumented Test Fill Evaluation," Proceedings of the 4th International Conference on Geotextiles, Geomembranes and Related Products, The Hague, Netherlands, 1990.

"Geosynthetics Play Critical Role in Simultaneous Construction of a Storm Water Retention Pond and a Reinforced Roadway Embankment," Geotechnical Fabrics Report, March/April, 1989.

Attachment 2 – Comment Tables

Review of PolyMet's Tailings Basin Permit Application: <u>Tailings Basin Dam</u>

Reviewers: Dirk Van Zyl, Steve Gale/Nate Lichty - Gale Tec Engineering, Inc. and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

#	Page	Section or Table Number	Comment/Concern	PolyMet Response	Final Comment	Recommendation			
						Address Pre-Permit	Address Post-Permit & Make Condition of Permit	Address Pre-constr.	Condition of Permit Recommendation
1	Geotech Report- page 123 Mgmt. Plan - page 5 Mgmt. Plan - page 34	Section 9 - Operat. & Mainten. Section 2.1- Flotation Tailings Charact. Section 6.3 - Adaptive Mgmt.	The Management Plan calls for the design and/or the operation to be modified based on operational experience using the Observational Method. We recommend that this approach be defined in the Permit similar to that included in a paper "Liquefaction of Tailings Dams" by Solseng, P.B. - Barr Engineering Company presented/published for a "Liquefaction of Mining Tailings" symposium in Cleveland, Ohio - 1997. The Barr paper details that the Observational Method concept design should include: 1) Predict behavior with detailed calculations, 2) design with contingencies, 3) construct with monitoring and 4) compare measurements with predictions and redesign if necessary. The Geotechnical Report Section 2.1-page 5 states that this method is used for all MDNR-Permitted Tailings Basins. If the Observational Method is to be permitted, we recommend that the plan include a design at the time of permitting and identify what instrumentation will be installed, where the instrumentation will be installed and what the instrumentation will monitor (e.g. excess pore water pressures and tailings dam deformations). If the Observational Method is permitted, we recommend that the permit require stability evaluations be submitted at least yearly with the annual Dam Safety Report. If a significant design change is required, we recommend that the company apply for a permit amendment.	Further clarification on the details of the Observational Methods were requested.	The Observational Method (Peck, R.B., Geotechnique, No. 2, 1969) is based on assessing potential geotechnical failure modes that may result during/post construction as well as conditions and events that could instigate instability. An example condition could be a previously undiscovered layer of soft soil beneath the dike alignment. An example event may be a large rainfall that causes increased seepage and slope toe erosion. After this assessment is complete and critical failure modes and conditions/events are identified and analyzed, contingency plans should be developed for each critical failure mode. We recommend this analysis be performed prior to construction. With the analysis results in mind, a monitoring system (geotechnical instrumentation, site reviews, etc.) should be developed and implemented during construction to monitor dike performance. The monitoring system would be used to confirm assumptions made during original design or to change operations/design if field observations and adverse measurements are recorded. We recommend that to adequately use this method for dike construction, that a geotechnical instrumentation and monitoring plan should be developed based on the results of the dike stability analysis that considers conditions/events that could result in localized or complete dike instability. Contingency plans should be developed for each critical condition. The instrumentation and monitoring plan should include 1) a list of geotechnical instruments that will be installed, where they will be installed and what they will be measuring, 2) how often the instrumentation readings be taken, 3) who will review the instrumentation readings, 4) what the typical values will be and what the thresholds will be that indicate "adverse conditions" that will require a change in operation or design. The contingency plan should include a list of potential adverse conditions that may occur and what would be observed if that condition occurred. The plan should include different operational/design options to address the adverse conditions.	X	X		The importance of a well defined Observational Method is paramount. It is the preference of the reviewers that this key issue be addressed as part of the permit application. Either as a pre-permit or as a condition of the permit, the following items need to be incorporated: 1) Adverse conditions/events that could lead to localized/global dike instability. 2) An instrumentation and monitoring plan that includes those items presented in "Final Comment" section. 3) A contingency plan that includes those items presented in "Final Comment" section.

Review of PolyMet's Tailings Basin Permit Application: Tailings Basin Dam

Reviewers: Dirk Van Zyl, Steve Gale/Nate Lichty - Gale Tec Engineering, Inc. and Stu Grubb/Cecilio Olivier - Emmons Olivier Resources, Inc.

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2	Mgmt. Plan - page 10 Geotech Report - page 75, Mgmt. Plan - page 10	Section 2.2.4 - Dam Construct. Section 6.3.2.4 - Cement Deep Soil Mixing Zone	Cement deep soil mixing (CDSM) shear walls are shown to be needed to satisfy stability of the north tailings dam as a result of liquefaction of buried slimes. The Geotechnical Report text states that a Construction Quality Assurance Plan will be developed. Since this CDSM structural feature is such a critical aspect of the plan, we recommend that the permit require bench-scale testing, test columns and field validation using such techniques as coring and wet sampling and geophysical testing (e.g. Ps logging and/or electromagnetic testing methods). The Federal Highway Administration (FHWA) has a design manual for Deep Mixing for Embankment and Foundation Support - October, 2013. This manual includes guidance for CDSM installation and integrity testing.	Post-permitting & pre-construct. bench scale testing and in-field validation testing is already incorporated in the construction specifications (FTMP, Attach. G, Section 313200). A Dec. 30, 2016 memo suggested that the CDSM be eliminated.	The Barr specifications included in the Basin Management Plan contain reasonable QA/QC procedures for CDSM construction.				This issue can be closed if a larger buttress will replace the CDSM.
3	Geotech Report - page 8 Geotech Report - page 41	Section 3.2 - Tailings Basin Develop. Section 5.2.3 - Shear Strength of LTVSMC Tailings and Table 5-10	The Report describes various peat layer thicknesses and various slime layer thicknesses beneath the Cell2E North perimeter dam. Sitka Corporation identified typical standard penetration resistance value (blow/foot) for the slimes was 5 or less and for the fine tailings was in the range of 15-20. We recommend that the layer thicknesses and the continuity of the layers be further investigated and a sensitivity analysis be performed based on the thickness, continuity and the liquefied shear strength values. A USSR liq=0.10 is included in Table 5-10 (page 41) for the LTVSMC fine tailings/slimes and further alludes to this value being a minimum to be used for design by the Engineering and Design Manual - Coal Refuse Disposal Facilities published by U.S. Department of Labor - MSHA. Further documentation should be provided for this value: and a sensitivity analysis should be performed in conjunction with the previously described parameters. Sitka Corporation found remolded vane shear strength values of the slimes to be in the range of 100 - 300 pounds per square foot. These low remolded vane shear strength values could indicate a USSR liq. less than 0.10. These lower values could result in a factor of safety of less than 1.1.	Slope stability sensitivity analyses to evaluate variation in material strength has been performed and reported in GDP Vol 1, Sections 6.6 and 7.3.8. Affirmation of selected strength parameters will be performed following acquisition of additional strength data during post-permit installation of instrumentation.	The additional subsurface exploration and instrumentation & monitoring plan should be developed based on the results of the analysis performed as part of the Observational Method process Part 1. The plan should include what instrument type is required, its location, depth and expected range of values that will be obtained during basin construction. This plan should be incorporated into the submittal discussed as part of Comment 1.	X	X		The additional subsurface exploration, performed post permit, and development of the Instrumentation and Monitoring Plan should be based on the analysis of critical failure modes as associated with Comment 1

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4	Geotech Report - page 8	Section 3.2 - Tailings Basin Develop.	The Report describes a layer of peat over a deposit of glacial till beneath the Cell 2E North perimeter dam. During the retreat of the glaciers approx. 10,000 years ago, depressions were formed in which lacustrine clay and peat were deposited. The Geotech. Report, however, does not reference any lacustrine clay layers, only peat over glacial till. Table 5-24 (page 64) identifies peat with a USSR yield = 0.23. This value may be appropriate for a fibrous peat but not for a decomposed amorphous peat or a high plasticity lacustrine clay. The soil types should be further investigated and sensitivity analysis performed for a range of shear strengths. Geotech. Report - page 49, Section 5.4.2.2, states that previous testing by Sitka resulted in higher permeability values for peat than that obtained from samples during the most recent 2014 investigation. This may indicate a different type of peat at various locations.	Same as Recommendation for Comment 3	The additional subsurface exploration and instrumentation & monitoring plan should be based on the results of the analysis performed as part of the Observational Method process Part 1. The results of this analysis should be used to develop the basin's instrumentation and monitoring plan. The plan should include what instrument type is required, its location, depth and expected range of values that will be obtained during basin's construction. This plan should be incorporated into the submittal discussed as part of Comment 1.	X	X		The additional subsurface exploration and instrumentation plan should be developed based on the analysis of critical failure modes as associated with Comment 1
5	Mgmt. Plan - page 22-24	Section 4.2 - Transport and Deposit. Plan	It appears that the stability analysis was based on maintaining a beach length of 625 feet between the inside crest of the dam and the edge of the water within the tailing basin. The water pocket could, at sometime during the operation, be closer to the dam than the 625 feet. Stability and exit seepage should be evaluated considering the water pocket closer or in contact with the tailings dam.	Addressed - have reviewed high pond conditions as shown in GDP Vol 1, Section 7.3.3.2 and supporting Sections	The analysis included a four foot head increase to the tailings basin water level while moving the water pond interface with the perimeter dike from 625 feet away to 150 feet away. Consistent with the Observational Method approach, a Contingency Plan should be prepared for instances when the water pocket is closer than 150 feet away from the inside crest of the dike. The April, 2017 Contingency Action Plan submitted by PolyMet/Barr should be updated to address this concern.	X	X		A Contingency Plan should be prepared as part of the Observational Method approach for circumstances when the water pocket is closer than 150 feet away from the inside crest of the dike
6	Mgmt. Plan - page 34	Section 7.3 - Structure Removals	The Management Plan is vague regarding abandonment of existing structures within the tailings basin and assumes that the previous owner properly abandoned all pipes within the basin which could be a conduit for water which could create erosion conditions which could then act as a trigger for liquefaction and induce a flow failure. Specifically, the 9 foot diameter drop inlet decant structure constructed in Basin 2W and the approximate 2000 lineal feet of 40 inch diameter spiral pipe extending into Basin 1E should be addressed.	This will be addressed post-permitting; prior to reactivation of the basin	If not investigated pre-permit, we recommend that the dam safety permit include language that requires all existing pipes/structures to be investigated and properly abandoned to ensure dike stability is maintained.			X	

Review of PolyMet's Tailings Basin Permit Application: Tailings Basin Dam

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7	Geotech Report - page 90	Section 6.6.1 - Range and Distrib. of Shear Strength Values	The Report identifies that sensitivity analyses were performed for the USSR properties for most of the soils using either a normal or log-normal distribution. However, a sensitivity analysis was apparently not performed for liquefied shear strength ratio (USSR) for the slimes. The Report identifies that based on previous geotechnical workshops, a single estimate of that particular strength was chosen. Apparently, the chosen ratio is 0.10. Using this ratio, 40 feet of overburden would result in a liquefied shear strength of 600 pounds per square foot. Residual vane shear testing has shown slime values as low as 100 - 300 pounds per square foot, which would result in a ratio of less than 0.10. We recommend that this issue be further explored.	Affirmation of selected strength parameters will be performed following acquisition of additional strength data during post-permit installation of instrumentation.	The additional subsurface exploration and instrumentation & monitoring plan should be based on the results of the analysis performed as part of the Observational Method process Part 1. The results of this analysis should be used to develop the basin instrumentation and monitoring plan. The plan should include what instrument type is required, its location, depth and expected range of values that will be obtained during basin construction. This plan should be incorporated into the submittal discussed as part of Comment 1.	X	X		The additional subsurface exploration and monitoring plan should be included and analyzed as part of the Observational Method and be as part of the submittal associated with Comment 1
8	Mgmt. Plan - page 37	Section 7.2 - Final Reclamat.	The Plan identifies approximately 3% bentonite by dry weight to be added to the fine tailings beach to a depth of 18 inches and then overlain by 30 additional inches of tailings and then vegetated. The 3% by dry weight addition should be further investigated based on field trials, not laboratory testing in which very controlled conditions exist. Closure of the pond bottom refers the Geotechnical Report reader to the Adaptive Water Management Plan - Version 7. The effectiveness of injecting bentonite through the pond water is subject to concern with regard to reliability of the infiltration reduction.	Pilot testing/field tests are already incorporated in closure construction specifications (FTMP, Attachment G, Section 03100)	A plan should be developed that requires test sections be constructed on both the pond bottom and tailings dike side slope to evaluate the chosen means for bentonite inclusion. The test section evaluation should consider: onsite water chemistry, potential for ice scour along the shoreline, oxidation of sulfide bearing rock within side slopes, and other concepts which may impact the permeability of the bentonite amended tailings. The Adaptive Water Management Plan, Section 5, states 3 methods on how the Tailing Pond bottom could be amended at the time of closure: 1) broadcasting granulated or pelletized bentonite on the pond surface and allowing it to settle to the pond bottom, 2) direct injection of bentonite into the pond bottom or 3) placing a GCL on the pond bottom. We understand that the PolyMet tailings are not available as yet for lab or field trials. But, if bentonite/tailing mixing (methods 1 or 2) is the preferred method of application, a preliminary material and installation specification should be developed and a protocol should be prepared for both a laboratory and a field pilot study as part of the permit application. The protocol (including the design calculations for 1 or 2) should include a degree of variability on which the acceptance criteria is based. The specification should also address how durability to ice heave on the side slopes and freeze-thaw degradation will be addressed.	X	X		Perform test sections for each bentonite application technology prior to tailings dike closure. A report should be submitted with test results and a QA/QC program demonstrating that the bentonite-tailings mixture has adequate permeability.

Review of PolyMet's Tailings Basin Permit Application: Tailings Basin Dam

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9	Geotech Data Package, Vol. 1, Attach. C, page 19	Section 3.0 - Drained Shear Strength Paramet.	The shear strength data for the different materials was evaluated by considering laboratory shear strength data plus interpreted field shear strength data from various tests as appropriate. The 33rd percentile of the resulting data was then selected for the stability analyses. In the case of the drained shear strength of the LTVSMC coarse tailings, the shear strength ranges are: laboratory testing 28 to 47 degrees, SPT testing 26 to 50 degrees and CPT testing 39 to 46 degrees (outliers below 39 degrees, to as low as 32 degrees were excluded, Figure A-3). The resulting value selected for stability analysis from the statistical analysis is 38.5 degrees. This value seems on the high side as lab testing and SPT testing values in the high 20's are included in the evaluation while lower values of the CPT testing were excluded. Furthermore, the drained shear strength selected for the coarse tailings is higher than that selected for glacial till - typically a well graded material that is very dense. The angularity of the coarse tailings particles might have played a role in the selection of this higher value. It is recommended that the stability analysis should also be done with a lower shear strength value, say 36 degrees, for the coarse tailings as part of a sensitivity analysis. It is recognized that this may not change the outcome very much, however this sensitivity analysis is an important aspect of developing further confidence in the effective strength stability results.	A sensitivity analysis will be performed to review the effect of the lower friction angles on dike stability. Strength data will also be further investigated during instrumentation installation.	The Dec. 30, 2016 Barr Memorandum identified no substantial reduction in the tailings dike global factor of safety by lowering the coarse tailings friction angle from 38.5 deg. to 36 deg. We question why some of the data was excluded from the statistical analysis and recommend that the coarse tailings friction angle be considered as a variable condition in the Observation Method process. At cross sections where lower friction angles result in lower factors of safety, the Observational Method would suggest enhanced instrumentation and monitoring at these locations. This analysis should be incorporated into the submittal discussed as part of Comment 1.	**X**	**X**		The apparent variability of the coarse tailings friction angle should be analyzed as part of the Observational Method and be a part of the submittal associated with Comment 1
10		Section 7.2 - Final Reclamat.	PolyMet is proposing a 20 year mine life and "wet closure" for the tailings basin. The proposed design is permittable and if permitted, would need to be managed in compliance with all rules and regulations including financial assurance. If permitted, the DNR should also require PolyMet to continually review the current state-of-the-practice for design techniques prior to starting any tailings basin closure activities. Information should be reviewed so that the decision on the best closure design option, accounts for current technologies, for environmental protections and considers the long term cost of operation. Continued study of tailings basin closure designs should also be considered as a permit condition. If a closure design change is required in the future, it must meet all environmental review and permitting standards.	Polymet will continue to evaluate potential project improvements during operations and at closure, one of which may be revisiting the tailings closure approach.	The review team is not ready to commit to a dry closure requirement. Wet closure will be more difficult and costly to manage for the long-term and it must be determined if this commitment is acceptable.			**X**	

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11		Barr Memo Dec. 30, 2016 on Tailings Basin Cell 2E Buttress Design as Alternate to CDSM	The modified buttress design includes increasing the buttress height by 35 ft. to a total height of 84 ft above the surrounding grade. This increased height will require the buttress slope toe to extend approx. 100 ft more into the wetland than what was previously proposed (200-250 ft total). The stability analyses presented are limited to global failure planes through the entire tailings dike. The stability analyses indicate that the peat will be removed from beneath the buttress. Localized stability of the buttress toe with a failure plane extending out into the virgin peat soils does not seem to have been evaluated. This localized failure could be significant in that it could result in a progressive failure into the buttress. The results of the stability analysis should be used to determine the buttress toe design. Potential adverse environmental effects associated with the buttress fill (e.g. wetland fill and geochemistry of the Area 5 material) will also need to be addressed.			**X**			

Review of PolyMet's Tailings Basin Permit Application: HydroMet Facility
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1	Mgmt. Plan - page 10	Section 2.2.2.2	The 80 foot high residue storage facility will be constructed over potentially soft ground. The management plan addresses shear strength gain and settlement of the soft soils but does not commit to a construction plan stating that the Observational Method will be used to assess what type of construction needs to take place in the future. Since the soft foundation soils already exist in place, these soils should be further tested and further evaluated such that a design can be promulgated. The pre-load method should be evaluated and a determination made if the pre-load will induce shear strength gain of the soft deposit and whether external drainage, such as wick drains, would be required. It is our opinion that the Observational Method requires a design be presented at the time of permit application.	The need for wick drains is dictated by schedule; the time available for pre-load construction relative to required in-service date for the HRF. The wick drains are not necessary for dam stability.	The subsurface exploration indicates that the soft ground beneath the proposed residue facility consists of up to 30 ft. of slimes, peat and tailings concentrate. The geotechnical report states that this material was placed hydraulically and therefore is likely in a loose unconsolidated state. A preload to consolidate the soft ground has been proposed to reduce settlement and subsequent strains that may occur in the proposed HRF Geomembrane liner. Wick drains are listed as optional based on the amount of time that a preload can be placed. The preload is proposed to be about 50 ft. in height, constructed in 5 lifts each 10 ft. thick. The top of preload elevation is given as 1,620 ft. in the project Plans, approximately 50 ft. above the existing grade of the emergency overflow basin. The top of dam elevation and residue elevation is proposed to be 1,650 ft. Due to the preload, the over consolidation ratio is estimated = 1.37 of the unconsolidated material. The preload is proposed to remain in place until instrumentation has indicated that pore pressure dissipation has been completed and that minimal additional settlement will occur. A 2 year preload time has been estimated. The geotechnical report indicates that the soft material will reenter the normally consolidated state during the last few years of residue filling. The settlement modeling that was performed assumes that the soft soil is isotropic, consisting of a uniform material. The model also varies the depth of the soft soil, but the soft soil depths are only known at a few discreet points where borings were performed, so there is likely some variability that is not expressed in the model. Due to the likely variation of material type and depth of the soft material, it is likely that differential settlement will occur over the length of the liner system, especially after the material becomes normally consolidated again during HRF construction. This variability may cause an excessive amount of strain in the liner system. The liner system has been designed based on an analysis which considers uniform subsurface conditions. If deformation from the preload construction varies notably from the predictions from this analysis, then the preload height, wick drain type and extent and the liner and leachate collection system design, in part, will have to be modified, as required. In accordance with the Observational Method approach, variability of parameters should be predicted at this time and alternate designs included in the Permit application. This would be necessary in order to establish appropriate financial assurance.	X	X		Design of the preload shall be required to reduce the potential for differential settlement and excess strain in the liner due to the underlying soft soils considering variable soil properties and variable deposit depths. It is recommended that this design be evaluated and approved prior to Preload/HRF construction
2	Mgmt. Plan - page 8	Section 2.2.2.1 - Liner and Leakage Collection System Design	The HydroMet residue basin will consist of a double liner with an internal leakage collection system. Since this system is susceptible to rupture as a result of strains in the geomembrane or geosynthetic liner as a result of settlement or other localized conditions, we recommend that the pre-load/wick drain system be further evaluated and a design promulgated for review during permit.	Deformation and impacts on liner were presented in GDP Vol 2, Sections 5.4 and 6.1	See Comment No. 1.	X	X		See Comment 1.
3	Mgmt. Plan - page 33 and 34	Section 7.2.2	The management plan identifies that the HydroMet closure will include a 40 mil LLDPE membrane or a MPCA approved geomembrane and a geosynthetic clay liner (GCL) constructed over a working platform. As far as we know, the MPCA does not have an approved geomembrane list. They do have a guidance on their website. We recommend that the liner type be further investigated and the proposed liner be identified and detailed at permit.	The proposed 40 mil LLDPE liner is detailed in the RMP, Section 2.2 and Attachments A and G.	This issue can be closed.				

WaterLegacy PTM Objections
Exhibit 15

RS33/RS65

Draft-01

February 21, 2007

RS33/RS65 – Hydrometallurgical Residue Characterization and Water Quality Model – NorthMet Project - DRAFT

Report Prepared for

PolyMet Mining Corp.

Report Prepared by

SRK Consulting
Engineers and Scientists

February 2007

RS33/RS65

Draft-01

February 21, 2007

RS33/RS65 – Hydrometallurgical Residue Characterization and Water Quality Model – NorthMet Project - DRAFT

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SRK Project Number 1UP005.001

February 2007

Table 5-2: Elemental Composition of Residues

Parameter	Unit	Leach, no $CuSO_4$	Leach, with $CuSO_4$	Gypsum	Raffinate Neutralization	Fe/Al	Mg	Combined	Combined no Gypsum
Ag	ppm	11.05	23.8	0.23	0.9	0.33	0.12	4.93	11.05
Al	%	2.82	1.97	0.02	0.02	0.46	0.03	0.54	1.01
As	ppm	35.4	56.3	3	6	15	5	110	34
B	ppm	<10	<10	<10	<10	<10	<10	<10	<10
Ba	ppm	40	30	<10	<10	<10	<10	10	20
Be	ppm	0.05	<0.05	<0.05	<0.05	0.28	<0.05	<0.05	<0.05
Bi	ppm	4.89	6.84	0.5	0.8	0.81	0.04	1.94	3.53
Ca	%	1.88	1.41	14.5	17.1	18.8	15.1	16.35	11.3
Cd	ppm	0.66	0.19	0.22	0.73	0.48	0.44	0.29	0.23
Ce	ppm	8.21	5.45	1.71	0.6	0.85	1.6	2.35	2.93
Co	ppm	133.5	17.9	5.1	9.3	105.5	13.6	6.9	23.6
Cr	ppm	112	154	8	11	457	5	59	116
Cs	ppm	0.1	<0.05	<0.05	<0.05	0.09	<0.05	<0.05	<0.05
Cu	ppm	7380	1280	184.5	22.5	2960	26.9	519	945
Fe	%	17.3	26.9	0.05	0.08	1.88	0.05	5.21	11.75
Ga	ppm	6.47	5.06	2.54	0.07	0.57	0.09	1.22	2.43
Ge	ppm	0.41	0.47	<0.05	<0.05	0.08	<0.05	0.11	0.22
Hf	ppm	0.12	0.06	<0.02	<0.02	0.12	<0.02	0.04	0.04
Hg	ppm	0.04	0.02	0.12	0.35	0.07	0.05	0.11	0.03
In	ppm	0.3	0.355	23.3	0.011	1.01	0.083	0.164	0.28
K	%	0.11	0.1	<0.01	<0.01	0.01	0.01	0.02	0.05
La	ppm	3.6	2.5	0.7	0.5	0.5	2.3	1.1	1.6
Li	ppm	1	0.6	0.1	0.1	0.5	0.5	0.2	0.2
Mg	%	0.28	0.25	0.01	0.01	0.14	9.44	0.39	1.47
Mn	ppm	35	<5	<5	5	23	83	<5	<5
Mo	ppm	21.8	28.4	0.47	0.85	42.3	0.38	9.35	18.9
Na	%	1.28	3	0.02	0.04	0.13	1.04	0.58	1.62
Nb	ppm	0.18	0.21	<0.05	0.06	0.46	0.06	0.11	0.17
Ni	ppm	3270	410	99.9	192.5	2710	1230	260	674
P	ppm	290	110	<10	20	160	40	70	90
Pb	ppm	48.5	56.1	8.3	86.1	20.4	12.5	133.5	32
Rb	ppm	1.7	1	0.2	0.3	0.5	0.3	0.4	0.7
Re	ppm	0.012	0.002	0.015	0.022	0.013	<0.001	0.009	0.009
S	%	5.47	9.22	>10.0	>10.0	>10.0	>10.0	>10.0	>10.0
Sb	ppm	1.22	1.81	0.18	1.25	1.47	0.4	3.99	1.14
Sc	ppm	1.3	0.8	0.4	0.4	4.4	0.5	0.8	1.1
Se	ppm	49.8	73.4	0.3	0.4	0.6	0.5	20.4	39.2
Sn	ppm	4.8	6.1	0.2	0.5	1.6	<0.2	2	3.2
Sr	ppm	73.1	63.9	60.6	106	83.7	86.5	77.3	85.2
Ta	ppm	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Te	ppm	2.01	2.91	0.01	0.07	0.09	<0.01	0.83	1.48
Th	ppm	1.1	0.9	<0.2	<0.2	0.3	<0.2	0.3	0.4
Ti	%	0.066	0.042	<0.005	<0.005	0.007	<0.005	0.012	0.019
Tl	ppm	0.1	0.34	0.03	0.03	0.24	0.02	0.06	0.19
U	ppm	0.06	<0.05	<0.05	<0.05	0.55	0.1	0.06	0.09
V	ppm	39	41	1	1	16	1	11	21
W	ppm	0.57	0.49	0.09	0.18	1.12	<0.05	0.26	0.45
Y	ppm	3.88	3.29	1.28	1.14	1.06	7.64	2	2.86
Zn	ppm	171	15	30	98	164	23	32	36
Zr	ppm	<0.5	0.7	1.5	4.2	1.2	<0.5	9.8	1.9

Table 5-3: Acid-Base Accounting Results

Parameter	Unit	Leach, no $CuSO_4$	Leach, with $CuSO_4$	Gypsum	Raffinate Neutralization	Fe/Al	Mg	Combined	Combined no Gypsum
Paste pH	-	2.6	3.3	3.8	5.4	4.6	9.6	-	9.4
Sulphur Forms									
Total S	%	6.24	9.8	19.55	18.95	17.9	14.4	16.5	13.65
S as SO_4	%, S	6.1	9.3	18.35	18.55	17.35	13.65	15.9	13.5
Calculated Sulfur Forms From XRD Mineralogy									
S as Gypsum	%, S	1.51	1.28	18.55	17.90	18.38	14.27	13.64	9.90
S as Natrojarsoite	%, S	4.49	8.32	0.00	0.00	0.00	0.00	1.27	3.87
Total SO_4	%, S	5.99	9.61	18.55	17.90	18.38	14.27	14.91	13.78
Calculated Sulfur Not Present as Calcium Sulfate									
Non-Gypsum	%, S	4.73	8.52	1.00	1.05	-0.48	0.13	2.86	3.75
Neutralization Potential									
Fizz Rating	-	1	1	1	1	1	3	1	2
Neutralization Potential (NP)	kg $CaCO_3$/t	-17	-4	0	0	-10	371	10	51
CO_2	%	-0.2	-0.2	-0.2	-0.2	-0.2	1.8	-0.2	0.3
C	kg$CaCO_3$/t	2	2	2	2	2	40	2	7
Acid Potential (AP)	kg $CaCO_3$/t	111	199	23	25	-11	3	67	88
Acid-Base Accounting									
NP-AP	kg $CaCO_3$/t	-164	-271	-38	-13	-27	348	-51	-72
NP/AP	-	-	-	0.0	0.0	-	124	0.1	0.6

Gypsum Residue

Gypsum residue is the first hydrometallurgical precipitation product. It is produced by limestone addition to the leach solution following recovery of platinum group metals and prior to copper recovery.

The elevated calcium and sulfate content of the gypsum residue sample confirmed that it was dominantly hydrated calcium sulfate. XRD showed that it was 99.8% gypsum.

The metal content of this residue was very low. Acid-base accounting indicated that the dominant sulfur form was sulfate. About 1.2% of the sulfur was not accounted for by sulfate analysis, but XRD failed to recognize any other sulfur minerals. It is likely therefore that the difference reflects analytical uncertainties rather than unknown mineral content.

Raffinate Neutralization Residue

This residue is formed by an intermediate neutralization step between copper removal and precipitation of iron and aluminum.

Facility Mercury Mass Balance Analysis (RS66)

PolyMet Mining Inc.

March 2007

Attachment A

POLYMET NORTHMET PROJECT, TOTAL FACILITY
MERCURY MASS BALANCE FLOW DIAGRAM
ZERO SURFACE-DISCHARGE YEAR-10 SCENARIO

Based on 32,000 st/day Ore Processed and 21.6 Hours per Day Operation for Process Plant

Product 0.05 **MSTPY** (million short tons per year)

Solids Throughput

Crushing/Milling:	11.7	**MSTPY**
Concentrating (output):	0.4	**MSTPY**
Flotation Tailings:	11.3	**MSTPY**
Hydrometalurgical Residue:	0.8	**MSTPY**
Process Consumables (at Concentrating):	1.414	**STPY**
Process Consumables (at Hydromet):	42.71	**STPY**

Liquids Throughput

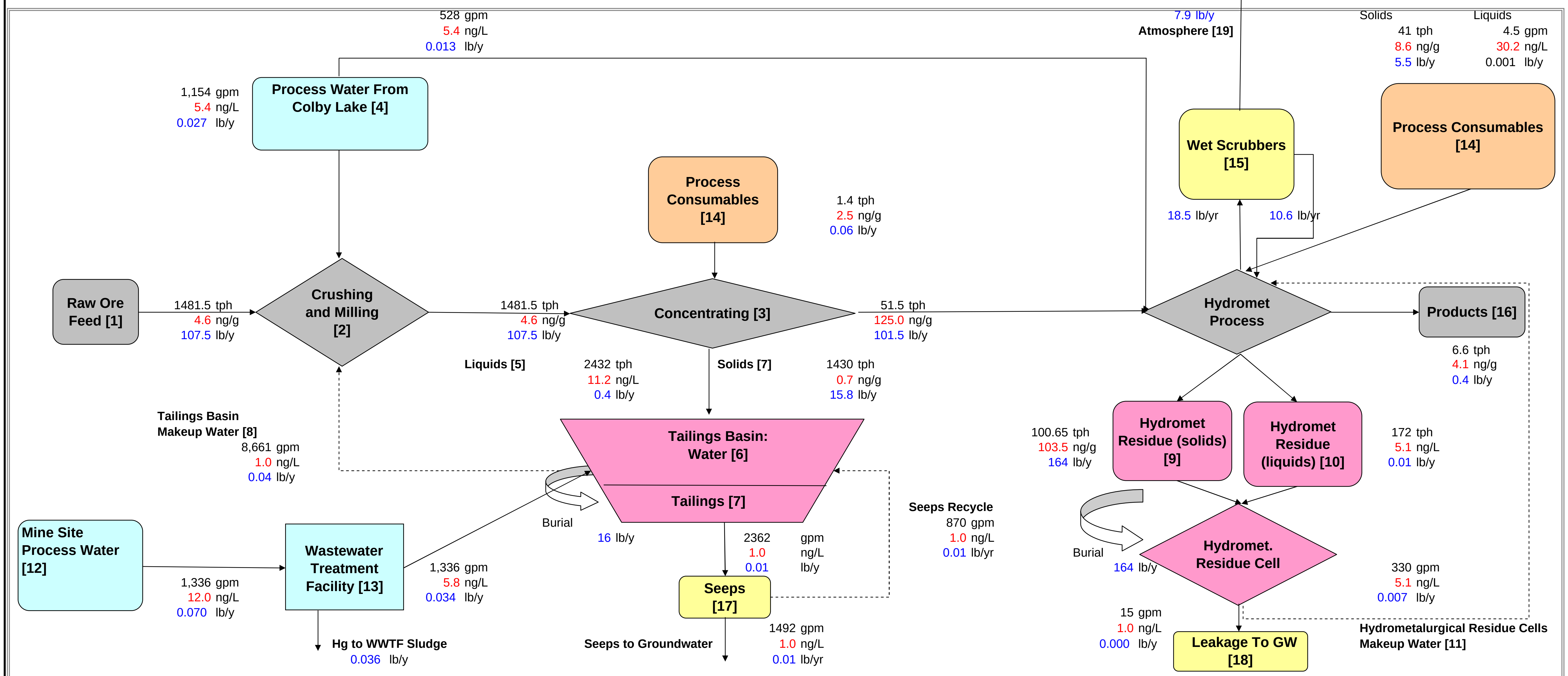
Process Water (From Mine):	1,336	**GPM**
Makeup Water (Tailings Basin):	8,661	**GPM**
Makeup Water (Hydrometalurgical Residue Cell):	330	**GPM**
Flotation Tailings (liquid):	19.2	**MSTPY**
Hydrometalurgical Residue (liquid):	1.4	**MSTPY**

Units

Throughput (tph)
Hg Concentration (ng Hg/g) or (ng/L)
Hg Annual Mass Load (lb Hg/y)
------- Recycle

	Hg Mass Balance Summary (lb Hg/y)					
	Total Input	Total Output	Output Constituents			
			Air	TB	HR	Product
Total Facility **[20]**	113	189	8.3	16.2	164.3	0.4

TOTAL AIR EMISSIONS:	**8.3**	**lb/y**
NATURAL GAS, CRUSHING, MINING, TAILINGS AIR EMISSIONS	**0.4**	**lb/y**
TOTAL GROUNDWATER DISCHARGE:	**0.01**	**lb/y**



Appendix C Footnotes:
Unless noted otherwise, Bateman Metals Throughput Data Based on MetSim Revision U3

[1] Raw Ore Feed
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: SGS Lakefield Research Limited, *Flotation pilot Plant Products Environmental Investigation and Air Testing* , LR10054-003 Progress Report No. 6, 2004 -- collected 10/4/2000
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x raw ore (st/y) x 2000 lb/st
2004 SGS Lakefield Progress Report used EPA Appendix to Method 1631. Ore samples from the 2005 Pilot Plant Study were analyzed using EPA 7641A. All 2005 ore samples were below the 20 ng/g detection limit (See RS 32 Pilot Plant Environmental Results -- Part 1, Liquids and Solids Sampling Flotation Report, Table 4, Ore Samples.) Thus, the composite sample from the 2004 Progress Report was used because low-level method is more accurate than an estimated concentration based on the 2005 Pilot Study non-detects.

[2] Crushing and Milling
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: Same as [1] above
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x crushed/milled ore (st/y) x 2000 lb/st
Less than .005 lbs per year Hg air emissions estimated from crushing and grinding operations; See RS57A for detailed emission calculations

[3] Concentrating
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: SGS Lakefield Research Limited, *Flotation pilot Plant Products Environmental Investigation and Air Testing* , LR10054-003 Progress Report No. 6, 2004 -- collected 10/4/2000
Concentrate samples from the 2005 Pilot Plant Study were analyzed using EPA 7641A. Although these 2005 concentrate samples were above the 20 ng/g detection limit (See RS 32 Pilot Plant Environmental Results -- Part 1, Liquids and Solids Sampling Flotation Report), Method 1631 data from ealier SGS pilot study used in order to be consistent with method 1631 data used for ore and flotation tailings [see note 7].
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x concentrate produced (st/y) x 2000 lb/st

[4] Process Water from Colby Lake
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: Polymet Mining, Inc., Polymet's Northmet Project, NTS Dunka Pit Sampling Data Report, 2005 (Includes sample from Colby Lake)
Mass Loading (lb/y) = water flow rate (gal/min) x 3.8 L/gal x 60 min/h x 8760 h/y x Hg concentration (ng/L) x 10^-9 g/ng / 453.6 g/lb

[5] Process Liquids to Tailings Basin (liquids)
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: RS 32 Pilot Plant Environmental Results -- Part 1, Liquids and Solids Sampling Flotation Report, Table 6, Process Water Samples; average of all parcels. Results below the detection limit included in average as half the detection limit.
Samples were taken from the process water tank. This water should be generally representative of water in the tailings basin.
Mass Loading (lb/y) = concentration (ng/L) x 10^-9 g/ng x tailing liquids (st/y) x 2000 lb/st x 3.8 L/gal / 8.34 lb/gal / 453.6 g/lb

[6] Tailings Basin Water
Existing Concentration Source: RS64 Existing Tailings Basin Water [Hg] is 1.0ng/g, Average of Cell 1E and 2E for 2002/2003.
Predicted concentration expected to also be less than or equal to 1.0 ng/L based on tests confirming tailings would adsorb mercury similar to taconite tailings, Bench-Scale Mercury Testing Report, May 2006 prepared by Northeast Technical Services, Inc.
Polymet is proposing a seeps collection system.
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x products produced (st/y) x 2000 lb/st

[7] Tailings (solids)
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: SGS Lakefield Research Limited, *Flotation pilot Plant Products Environmental Investigation and Air Testing* , LR10054-003 Progress Report No. 6, 2004 -- collected 10/4/2000
The 2004 SGS Lakefield Progress Report study used EPA low-level method (Appendix to Method 1631) for solids.
Flotation tailing samples from the 2005 Pilot Plant Study were analyzed using EPA 7641A. Most of these 2005 tailings samples were below the 20 ng/g detection limit, with some high data points (See RS 32 Pilot Plant Environmental Results -- Part 1, Liquids and Solids Sampling Flotation Report). The result is a 47 ng/g average concentration as a Windsorized mean of log transformed data, accounting for a suspected outlier value.
However, using 47 ng/g would result in about eight times more mercury being sequestered in tailings basin than input with the ore. Therefore, data from the earlier SGS Report (2004) composite sample based on Appendix to Method 1631 was used in the mercury balance (0.7 ng/g).
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x tailings (st/y) x 2000 lb/st
Approximately 0.1 lbs/year Hg air emissions estimated due to wind erosion not shown in diagram.

[8] Makeup Water from Tailings Basin
Throughput Source: Polymet (via Bateman Metals) with adjustments made by Barr Engineering to reflect project water balance.
Concentration Source: Assumed concentration in makeup water is same as concentration in tailings basin water
Mass Loading (lb/y) = water flow rate (gal/min) x 3.8 L/gal x 60 min/h x 7884 h/y x Hg concentration (ng/L) x 10^-9 g/ng / 453.6 g/lb

[9] Hydrometalurgical Residue (solids)
Solids include filter cakes. Hydromet Residue Cells are lined treatment cells, separate from the Flotation Tailings Basin
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: Pilot Plant Envrionmental Sampling and Analysis, Hydrometallurgical Process Liquids and Solids Sampling Results; RS32 Part 3.
Weighted average concentration calculated from data for Mg Residue, Raffinate Neutralization Gypsum, Neutralization Gypsum, and leach residue. Values below the detection limit were assigned a value of 1/2 the detection limit.
Note: Fe/Al removal residue was also collected during the pilot plant. This step has been eliminated from the process and the Fe/Al and presumably any trace mercury would be preciptitated in the raffinate neutralization gypsum per Bateman.
The weighted average Hg concentration in the raffinate neutralization/Al-Fe removal residue was calculated based on relative residue generation rate data in Table 4.1 of RS33/RS65.
Mass Loading (lb/y) = concentration (ng/g) x 10^-9 g/ng x hydromet residue (st/y) x 2000 lb/st

[10] Hydrometallurgical Residue (liquids)
Liquids include entrained filter wash water and liquid in Mg precipitation slurry. Hydrometalurgical Residue Cells are lined treatment cells, separate from the Flotation Tailings Basin
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: Envrionmental Sampling and Analysis, Hydrometallurgical Process Liquids and Solids Sampling Results; RS32 Part 3, Table 6 Magnesium Overflow Analytical Data Summary.
The water from the magnesium thickener overflow is respresentative of the major source of water in the residues. The current plant design has the magnesium slurry being blended with the other residues and sent to the lines cells without the use of a thickener. However, the end result is the same.
Mass Loading (lb/y) = concentration (ng/L) x 3.785 L/gal / 8.34 lb H20/gal * 2000 lb/ton x 10-9 ng/g / 453.6 g/lb * water to hydrometallurgical residue celss (st/hr) x 7884 hours/yr

[11] Makeup Water from Hydrometalurgical Residue Cells
Throughput Source: Polymet (via Bateman Metals) with adjustments made by Barr Engineering to reflect project water balance
Concentration Source: Makeup water assumed to have same mercury concentration as Magnesium Thickener overflow described in Note [10] .
Mass Loading (lb/y) = water flow rate (gal/min) x 3.8 L/gal x 60 min/h x 8760 h/y x Hg concentration (ng/L) x 10^-9 g/ng / 453.6 g/lb

[12] Process Water from Mine
Throughput Source: RS13 Tailings Basin Water Balance for year 10. Proportion of process water from mine and make up water from Colby Lake will vary by year, but this will not have a significant impact on the Hg balance.
Concentration Source: RS29T Mine Pit Water Quality Model
Mass Loading (lb/y) = water flow rate (gal/min) x 3.8 L/gal x 60 min/h x 8760 h/y x Hg concentration (ng/L) x 10^-9 g/ng / 453.6 g/lb

[13] Process water from Mine Water Treatment Plant (To be located at Mine Site)
Mine water to be treated for metals, hardness, other; water quality will match that in tailings basin; See EIS Study Reports RS29T for details on wastewater treatment technology and effluent concentrations.
Concentration Source: RS29T Wastewater Treatment Technology; 50% mercury removal assumed.
The small amount of Hg in WWTF sludge would be reintroduced into Hydrometalurgical Plant (to recover metals) or disposed of in Hydrometalurgical Residue Cells

[14] Process Consumables
Process Consumables added at Concentrating are similar to blended reagent sample

Consumable Name	Throughput (tph)	Where Added in Process	Included in Blend of Reagent Sample?	Specific Gravity	Concentration (ng/g)	Concentration ug/l	GPM
PAX - Collector	0.68	Concentrating	Yes	1.15			
MIBC - Frother	0.031	Concentrating	Yes	0.87			
DF 250 - Frother	0.010	Concentrating	No		2.25		
CuSO4	Recycled from EW	Concentrating	No				

Flotation Flocculant - M10	0.693	Concentrating	Yes	ND		0.0048	
Concentrating Total	**1.4138**						
Hydromet Solid Reagents							
Sodium Hydrosulfide (NaHS)	0.331	Hydromet Process	No		10		
Guar Gum	0.00128	Hydromet Process	No		ND		
Leach Residue Flocculant - 351	0.0284	Hydromet Process	No		10		
Hydrochloric Acid (NaCl in Pilot)	2.528	Hydromet Process	No		8.3		
Cobalt Sulphate (CoSO4)	0.00088	Hydromet Process	No		ND		
Plant Flocculant - M 342	1.40E-05	Hydromet Process	No	ND	10		
Coagulent - M368	1.69E-05	Hydromet Process	No		10		
Magnesium Oxide	4.47	Hydromet Process	No		10		
Limestone	31.88	Hydromet Process	No		8.3		
Lime	1.6	Hydromet Process	No		10		
Hydromet Solid Total	**40.839591**						
Hydromet Liquid Reagents							
Sulfuric Acid	1.36	Hydromet Process	No	1.76		0.002	3.077362
Diluent	0.017	Hydromet Process	No	0.819	1.29		0.085249
Extractant	0.003	Hydromet Process	No	0.96	1.29		0.010818
Liquid SO2	0.481	Hydromet Process	No	1.43	ND	ND	1.343509
Caustic	0.00839	Hydromet Process	No	1.5	ND	ND	0.022341
Hydromet Liquid Total	**1.87**						**4.539279**

Throughput Source: Polymet (via Bateman Metals (DFS Exectutive Summary and General and Process Design Criteria spreadsheet (Rev E1)provided by Bateman)); Note: concentration reagent throughputs was adjusted to reflect solution concentrations as described in General and Process Design Criteria spreadsheet because samples consisted of decanted, filtered liquid from the solutions used in the pilot study.

Concentration Source: Combined Flotation Reagent Sample: SGS Lakefield Research Limited, LR10054-003 Progress Report No. 6, 2000; average of disolved Hg concentration. Note: samples were filtered prior to analysis so any mercury in a solid phase would not be detected.
Barr also sampled the flotation flocculent during the 2005 pilot study. This sampling produced a slightly lower result, so the combined sample result was used. Note: reagents changed somewhat between 2000 and 2005 pilot plants.
Data for hydromet plant consumables taken from Envrionmental Sampling and Analysis, Hydrometallurgical Process Liquids and Solids Sampling Results; RS32 Part 3. A weighted average concentration was calculated for all reagents sampled.
NaCl was used in the pilot plant, while HCl will be used in the commercial scale plant. Different flocculents and/or coagulents may be used in the commercial scale facility. Liquid SO2 was not used during the pilot study, Hydrogen peroxide was used in the pilot scale plant but will not be used in the full scale plant; results were below the detection limit and were not included in the weighted average. Data was not obtained for CoSO4 and guar gum during the pilot study.
The concentration for compounds for which data was not obtained was assumed to the same as the weighted average of those for which data was obtained. The HCl usage rate from the design criteria spreadsheet was adjusted to reflect NaCl use in the pilot plant based on molecular weight.
Separate weighted averages were calculated for hydromet liquid and solid reagents.

Mass Loading liquids (lb/y) = liquid reagent flow rate (gal/min) x 3.8 L/gal x 60 min/h x 7884 h/y x Hg concentration (ng/L) x 10^-9 g/ng / 453.6 g/lb

Mass Loading Solids (lb/y) = solid usage rate (tph) * 2000 lb/ton * 453.6 g/lb * Hg concentration (ng/g) * 10^-9 g/ng * 7884 hr/yr

Specific gravity data used where necessary to convert mass flows to volume flows. Data obtained from General and Process Design Criteria Spreadsheet obtained from Bateman.

[15] Autoclave Wet Scrubbers
Emission calculations: RS57A. 25% control assumed for autoclave vent emissions. 72% control used for autoclave flash vent emissions, based on data from SGS 2005 Pilot Plant Study using EPA Method 29 for air emissions (Pilot Plant Environmental Results, RS 32, Part 4). Overall scrubber weighted control efficiency of 58% for Hg.
Oxidizing conditions in autoclave likely to drive Hg toward Hg2+ form; therefore, control efficiency for autoclave emissions likely to be higher than 25%.
Mercury captured in scrubber water is returned to hydrometalurgical process, where oxidized form likely goes to hydromet residue solids.

[16] Products
Throughput Source: Polymet (via Bateman Metals)
Concentration Source: Envrionmental Sampling and Analysis, Hydrometallurgical Process Liquids and Solids Sampling Results; RS32 Part 3. Appendix C RS28T. Weighted average concentration calculated from data for MHP and PGM Concentrate;
Results below detection limit assigned a value of 1/2 the detection limit. Copper cathode not analyzed; assume no mercury present.

[17] Aproximately 35% of seeps from the tailings basin will be recycled in year 10; other years will vary. The balance will seep to the groundwater. See Tailings Basin Water Balance, RS13
Seepage to groundwater assumed at least 1 to 5 minutes of contact with tailings and associated reduction in mercury concentration in water to 1.0 ng/l, source: Bench-Scale Mercury Testing Report -May 2006 prepared by Northeast Technical Services, Inc.

[18] Throughput Source: Polymet Hydrometalurgical Plant Water Balance
Concentration Source: Mercury in leakage from residue cells expected to be the same as from tailings basin because leakage would flow through LTV tailings before reaching groundwater.

[19] Potential Emissions to Atmosphere; Future estimated actual emisisons are 7.3 lb/yr.
Concentration Source: RS 32 Pilot Plant Environmental Results -- Part 1, scaled up to full plant operation (see RS57A). Overall 58% scrubber control efficiency based on autoclave exhaust sampling results from 2005 pilot study,
Aproximately one-half of estimated emissions based on non-detect values, in which one-half detection limit used to calculate emission rate. See note 15 for mercury control assumptions.

[20] As with other mining facilities, there is uncertainty regarding the amount of mercury in the solids and the air emissions from the proposed project. In this case. Additional measurements of mercury in ore, concentrator tailings, residue and other sources and sinks will be completed following project start-up.

Summary Analysis of
PolyMet NorthMet Modeled Tailings Chemistry
and MinnAMAX Site Tailings Leachate
Prepared for Water Legacy

Bruce Johnson, Chemist/Biologist, Retired Regulator

December 2015

I am a chemist/biologist and retired regulator with extensive field and technical experience in environmental impacts of copper-nickel sulfide mining and peat mining, remediation of water quality impacts, and compliance with state and federal regulations. I was the field chemist in charge of metals pathway analysis for Minnesota's Regional Copper-Nickel Study, the field chemist researching metal sulfide leachates from the MinnAMAX (AMAX) waste rock and tailings piles, and the land reclamation specialist responsible for construction of these AMAX test piles.

In reading various versions of the PolyMet NorthMet (PolyMet) environmental impact statement and its supporting documents, I have been troubled both by the low solute concentrations predicted by PolyMet for the tailings seepage and by the fact that the documents used the AMAX waste rock pile leachate as a reference source, but drew no data from the AMAX tailings test pile, an appropriate reference for the PolyMet tailings.

It is my opinion that the PolyMet final environmental impact statement and underlying documents, including the Water Management Plan for the Plant (PolyMet 2015i) underestimates the likely concentrations of solutes in NorthMet tailings toe seepage, in some cases by more than an order of magnitude.

In response to Comment ID 17802, FEIS p. A-112, it is stated, "The FEIS relies on AMAX-derived data in a variety of circumstances." Examples were listed, such as scaling humidity cell results with AMAX waste rock leachate data. Yet, PolyMet does not use the AMAX tailing data to scale their tailing seepage modeling predictions. Instead the Co-Lead Agencies discount the value of the MDNR's own AMAX tailings data to predict PolyMet seepage concentrations, by stating the AMAX shaft is "many miles away" (FEIS p. 5-131), (It is 3.2 miles away only half a mile more than the length of the PolyMet mine, and the closest actual copper–nickel sulfide tailing~~s~~ data) and, "it is uncertain if geologic units and structures penetrated by the shaft are similar to those in the location of the NorthMet Project Proposed Action" as in the response to Comment 17800, p. A-111 (It is in the same Partridge River Formation rock).

I briefly summarize the conditions under which AMAX tailings leachate was produced and the results of my comparison of AMAX data to PolyMet tailings seepage modeling predictions. Modeling loses it credibility when there is no field verification from appropriate field source data.

The AMAX tailing leachate data was derived from tailings that were processed by the Twin Cities Research Center of the U.S. Bureau of Mines from crude ore samples collected from the Duluth Complex formation at the AMAX site (Schluter and Mahan 1981). The tailings were processed using a bulk flotation process. Sodium isopropyl xanthate and MIBC (methyl isobutylcarbonol) were used in the flotation circuit, as collector and frother, respectively. An unspecified conditioner was also added to the circuit. The mineralogy of the tailings was not analyzed, but it would be expected to be similar to that of the initial ore. This is very similar to the process chemicals proposed by PolyMet. The ore was approximately 40 to 70 percent plagioclase, with about 15 to 40 percent combined olivine, pyroxene and amphibole (Stevenson et al. 1979).

Chlorite, biotite and smectite have each been found in ore at levels less than 5 percent (Stevenson et al. 1979). Some of the trace metals in the Duluth Complex do not occur as discrete metal sulfides, but are included within olivine, pyroxene and plagioclase (Iwasaki et al. 1982).

In November 1978, a tailings plot approximately 20’ x 30’ x 2’ deep, was constructed. A 30-mil Hypalon synthetic liner was placed beneath the tailings to prevent seepage and provide an impermeable base for a drainage collection system. The AMAX tailing processed by the U.S. Bureau of Mines were placed on top of the liner and final grading was done using hand tools to smooth the surface and provide a depth of approximately 50 cm. Leachate from the plot was collected for three years. Data was reported in 2004 by MDNR in a report entitled *Drainage from Copper-Nickel Tailings: Summary of a Three-Year Field Study*, July 2004, a copy of which is attached. The report notes that a short-circuiting of the liner allowed some rainwater to avoid traveling totally through the tailing producing some very low results that would not be representative. However the mean and median averages are likely to be representative of copper-nickel tailings leachate. Many values are elevated as compared to values from taconite ore tailings in Northeast Minnesota mines.

Tables 1 and 2 of this report, compare PolyMet’s Estimated Tailings Basin Seepage Water Quality from the North Toe, (PolyMet 2015i, Large Table 2, Attachment A) with the values from the AMAX tailing. Both AMAX and PolyMet are in the Partridge River Duluth Complex Formation. PolyMet found it reasonable to use the AMAX waste rock test plots to provide a source calibration for their waste rock humidity tests. Thus comparing AMAX tailing from the same source is reasonable; yet it has not been done.

Table 1 provides the AMAX maximum, mean and median of the observed data and the P10, P50, and P90[1] predictions for maximum concentration levels in seepage at the North Toe of the PolyMet tailing basin for the first five years of production in PolyMet modeling (PolyMet 2015i, Large Table 2). Even the AMAX mean and median data for many solutes far exceeds PolyMet's probability predictions, keeping in mind AMAX measurements occurred in just 3 years of testing versus PolyMet's 5-year model predictions.

Table 2 compares the PolyMet P90 maximum predicted concentrations of the tailing leachates in the first 5 years of production (from PolyMet 2015i, Large Table 2) with the AMAX tailing test plot maximum observed concentrations. Even if the chloride ratio is considered to be an anomaly, an assumption that may be inaccurate (See Johnson opinion on the SDEIS, 2014), maximum levels of metals and salts in the AMAX tailings leachate are far higher than what was modeled for the PolyMet project. Leachate from AMAX tailings contained maximum levels of cobalt more than 30 times the P90 maximum predicted for the NorthMet project, levels of nickel more than 21 times the P90 predicted PolyMet concentrations, levels of sodium 35 times the P90 predicted PolyMet concentrations, and levels calcium, magnesium and sulfate more than 11 times higher than predicted P90 maximum PolyMet concentrations.

PolyMet's predictions affect the conclusions in the FEIS regarding biological impacts and ecological impacts of changes in water quality. Data from the existing AMAX three-year tailing field study calls into question assumptions in the FEIS that tailings seepage would not adversely affect water quality or violate Class 2B standards to protect aquatic life.

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[1] P90 is defined in the FEIS Glossary as "90th percentile probability, which means that there is at least a 90 percent probability that a constituent would not exceed the evaluation criteria."

TABLE 1 MinnAMAX Tailing Leachate Data and PolyMet Tailing Leachate Modeling Predictions							
		AMAX* Measured Leachate (3 year field study)			PolyMet Prediction NorthMet Tailings Seepage (mine year 5 North Toe)**		
Parameter	**Units**	**Max**	**Mean**	**Median**	**P10 Max**	**P50 Max**	**P90 Max**
Calcium	mg/l	600	329.06	388	45.65	45.93	46.32
Magnesuim	mg/l	954	243.48	212	79.78	80.29	80.66
Sodium	mg/l	2500	467.3	277.5	70.29	70.79	71.21
Potassium	mg/l	102.2	45.8	40.5	10.12	10.21	10.31
Sulfate	mg/l	3,950	1752	1750	335.79	338.29	340.16
Chloride	mg/l	4,690	890	433	22.26	22.45	22.65
Manganese	ug/l	920	198	70	368.82	391.24	415.29
Nickel	ug/l	430	172	170	8.24	12.42	20.47
Copper	ug/l	170	59	60	16.03	21.79	29.75
Cobalt	ug/l	90	35	35	2.32	2.55	2.99
Zinc	ug/l	30	19	20	14.53	15.01	15.74
Iron	ug/l	80	38	40	3,838.08	3,869.43	3,893.63

TABLE 2 Comparison - MinnAMAX Leachate Data and PolyMet 5-year Predictions				
Parameter	**Units**	**AMAX Tested Maximum**	**PolyMet Modeled P90 Max**	**Ratio AMAX/ PolyMet**
Calcium	mg/l	600	46.32	12.95
Magnesuim	mg/l	954	80.66	11.83
Sodium	mg/l	2,500	71.21	35.11
Potassium	mg/l	102.2	10.31	9.91
Sulfate	mg/l	3950	340.16	11.61
Chloride	mg/l	4960	22.65	218.98
Manganese	ug/l	920	415.29	0.50
Nickel	ug/l	430	20.47	21.01
Copper	ug/l	170	29.75	5.71
Cobalt	ug/l	90	2.99	30.10
Zinc	ug/l	30	15.74	1.91
Iron	ug/l	80	3,893.63	0.02

* MDNR, Drainage From Copper-Nickel Tailings:Summary of a Three-Year Field Study, 2004, Table 7
**Water Modeling Data Package, Vol. 2 - Plant Site, PolyMet 2015i, Large Table 2

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Attachment A	PolyMet 2015i Large Table 2.
Attachment B	MDNR, Drainage from Copper-Nickel Tailings: Summary of a Three-year Field Study, July 2004.

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Chemist/biologist, retired regulator with extensive field and technical experience with environmental impacts of copper-nickel sulfide mining and peat mining, remediation of water quality impacts, compliance with state and federal regulations.

Employment

(1990-2004) Minnesota Department of Transportation

- Supervisor of Environmental Investigations and Compliance Unit
- Supervised all the Department's Superfund, Petrofund, Hazardous and Solid Waste Management;
- Developed a waste management and environmental audits program to reduce environmental liabilities;
- Developed a unique method to compost petroleum contaminated soils;
- Developed environmentally safe methods to remove and legally dispose hazardous lead based paint from bridges within the state;
- Reduced the Department's hazardous waste production 84%, from a large quantity generator to a small quantity generator;
- Developed a program to safely and legally remove abandoned hazardous waste from state administered transportation properties;
- Eliminated use of lead and chromium based paints as roadway striping while maintaining US/DOT requirements for reflectivity.
- Drastically reduced the use of treated wood in highway guard rails;
- Developed a chemistry baseline for heavy metals concentrations in high way rights-of-way in the Twin Cities metropolitan area;
- Assessed the potential environmental chemical and biological impacts from using waste tires as a light-weight fill in roadway construction;
- Developed chemical and biological procedures to test new products for potential environmental impacts prior to full-scale implementation.

(1984-1990) Minnesota Pollution Control Agency – Pollution Control Specialist Intermediate, Industrial Enforcement Team Leader

- Technical leader for the NPDES industrial enforcement unit staff;
- Enforced NPDES industrial permit requirements for all state industries;
- Enforced all NPDES Mining Permits;
- Developed statewide permit conditions for the land application of cannery wastes;
- Water quality lead staff to enforce environmental crimes.

(1979-1984) Minnesota Department of Natural Resources
Minerals Supervisor, Peat Mining Study of the environmental impacts from a test peat mining operation near Cotton, Minnesota.

- Researched potential water quality impacts from a pilot fuel peat mining operation;
- Developed sampling protocols to assess impacts from the state's test fuel peat mining program;
- Analyzed project chemical data from study;
- Co-author of the study report.

Hydrologist II, Peat Mining Research

- Developed and designed monitoring and methods to comply with regulations
- Developed plan and quality assurance for compliance with NPDES permit

Land Reclamation specialist for MinnAmax test piles construction
Field Chemist in charge of the MinnAmax metal pathways field study of environmental impacts from sulfide mining.

- Researched metal sulfide metal leaching mechanisms;
- Developed sampling protocols to assess impacts from sulfide waste rock and tailing field test plots;
- Insured chemical quality control quality assurance is maintained;
- Analyzed project chemical and water volume data;
- Assisted in developing project reports.

(1976-1979) State of Minnesota - Regional Copper Nickel Study
Field Chemist in charge of metal pathways portion of analysis, including:

- Researched sulfide metal leaching mechanisms;
- Assessed chemical data;
- Assessed water quality impacts from Erie Mining Company's Dunka mine sulfide waste rock leachates;
- Developed sampling protocols to assess potential water quality impacts
- Develop sediment sampling protocols to assess ambient metal concentrations in lake sediments;
- Surveyed existing lake sediments for ambient heavy metal concentrations;
- Surveyed selected bulk sample sites for leachate impacts;
- Assisted in developing project reports.

(1973-1976) U.S. Environmental Protection Agency
Shagawa Lake Eutrophication Project.
Assisted in assessment of remediation of a lake impacted from municipal sewage resulting in hyper-eutrophic conditions. Operated a carbon-14 primary productivity laboratory; developed in situ sediment sampling procedures; analyzed data.

(1972-1979) U.S. Army
First Lieutenant, Chemical, Biological, and Radiological Staff Officer.

Education & Certifications
1969 **B.A. - Biology/Chemistry** - Winona State University
1972 **B.S. - Education** - Winona State University

Hazardous Waste Investigations Training, U.S. Department of the Treasury, Federal Law Enforcement Training Center, Glencoe GA.

Certified Hazardous Materials Manager - Masters level. Certified by: Academy of Hazardous Materials Managers

Professional Recognition:
2000 MPCA Award for Northern Minnesota Abandoned Hazardous Waste Pilot Project,
1990 MPCA Meritorious Service Award
1990 Letter of Appreciation, Attorney General Office State of Minnesota

1990 Letter of Recognition, Attorney General State of Minnesota

Publications:

Decision Support Model for Assessing Net Public Benefits of Reuse of Waste Materials in Highway Maintenance and Construction, Hyman, Johnson, 2001.

Hazard Analysis And Risk Management Of Road Subbase Materials Using The Comparative Risk Bioassay Methodology, Johnson Belluck, Melby, 1997.

Comparative Risk Bioassays for Determining the Relative Hazards of Recycled Materials, Johnson, Belluck, Melby 1996.

A Comparative Study of the Toxicity of Shredded Tires and Wood Chips using the Biological and Chemical Comparative Risk Methodology, Johnson, Belluck, 1996.

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Hydrologic and Water Quality Monitoring of a Fuel Peat Mine Near Cotton, Minnesota, Eger, Lapakko, Johnson, 1985.

Environmental Leaching of Duluth Gabbro Under Laboratory and Field Conditions: Oxidative Dissolution of Metal Sulfide and Silicate Minerals, Eger, 1980. (Contributor)

Additional Professional Activities:
2006 - present. Chairperson, Isanti County Water Board that sets policy for surface and ground water management in the County.

2002 – present. Owner of bandsaw mill and hardwood specialty sales business, designed and installed solar panels, solar hot water wood kiln and two wind generators.

1996 – 2000 National Academy of Sciences, Transportation Research Board member of the Environmental Maintenance Subcommittee.

1990 Republic of Germany - 5-week working internship with the Umwelt Bundes Amt (German Federal EPA) to share environmental scientific expertise.

1979 –1981, Owned, designed and engineered a unique, energy efficient 7000 sq. ft. hydroponic greenhouse that included designing the nutrients used in the facility.

Large Table 2 Estimated Tailings Basin Seepage Water Quality from the North Toe

Constituent	Mine Year	Mine Year 5			Mine Year 20			Mine Year 30			Mine Year 60			Mine Year 100		
	Percentile / Units	Average P10(1)	Average P50(1)	Average P90(1)	Average P10(1)	Average P50(1)	Average P90(1)	Average P10(1)	Average P50(1)	Average P90(1)	Average P10(1)	Average P50(1)	Average P90(1)	Average P10(1)	Average P50(1)	Average P90(1)
Ag (Silver)	µg/L	0.16	0.17	0.17	0.19	0.19	0.20	0.18	0.18	0.19	0.15	0.16	0.18	0.15	0.16	0.18
Al (Aluminum)	µg/L	11.46	11.54	11.60	1.47	1.79	2.16	2.23	3.44	4.54	2.80	5.68	8.69	2.92	6.35	9.87
Alkalinity	mg/L	242.65	244.20	245.41	49.11	55.05	60.04	70.48	85.86	95.42	78.91	89.32	99.07	78.12	88.98	99.46
As (Arsenic)	µg/L	4.91	5.01	5.15	49.69	52.89	55.74	19.59	21.35	23.79	23.82	26.28	28.87	25.75	28.33	30.97
B (Boron)	µg/L	296.57	298.13	299.34	109.63	112.92	118.12	132.64	141.78	155.63	164.05	181.46	198.99	174.23	195.10	215.06
Ba (Barium)	µg/L	162.58	163.52	164.23	20.17	20.89	21.83	22.17	22.87	24.60	26.68	27.64	29.07	29.93	30.96	32.30
Be (Beryllium)	µg/L	0.29	0.29	0.29	0.39	0.40	0.41	0.39	0.41	0.44	0.35	0.42	0.49	0.35	0.44	0.52
Ca (Calcium)	mg/L	45.65	45.93	46.32	148.07	198.65	267.34	104.05	127.67	147.93	77.52	91.15	106.25	77.02	91.06	108.19
Cd (Cadmium)	µg/L	0.19	0.19	0.21	1.18	1.79	3.85	1.16	1.45	2.00	0.68	0.87	1.81	0.49	0.65	1.56
Cl (Chloride)	mg/L	22.26	22.45	22.65	25.28	27.76	32.33	21.28	23.35	27.44	14.54	15.83	17.76	11.92	12.99	14.33
Co (Cobalt)	µg/L	2.32	2.55	2.99	13.19	27.77	65.34	9.73	19.33	34.72	5.67	10.91	22.02	4.64	9.26	20.69
Cr (Chromium)	µg/L	0.68	0.72	0.78	5.97	6.28	6.58	3.07	3.28	3.71	2.83	3.07	3.34	2.40	2.63	2.90
Cu (Copper)	µg/L	16.03	21.79	29.75	310.47	473.97	649.85	282.63	426.45	591.80	245.81	375.91	514.67	248.04	376.15	509.79
F (Fluoride)	mg/L	3.72	3.74	3.75	1.11	1.18	1.26	0.70	0.76	0.89	0.42	0.45	0.50	0.31	0.33	0.35
Fe (Iron)	µg/L	3,838.08	3,869.43	3,893.63	149.26	178.61	206.18	226.23	314.99	394.71	412.25	651.70	852.42	437.38	717.67	945.69
K (Potassium)	mg/L	10.12	10.21	10.31	33.99	35.20	36.30	25.05	26.54	28.33	20.61	22.11	23.58	17.90	19.35	20.72
Mg (Magnesium)	mg/L	79.78	80.29	80.66	75.40	84.46	96.28	72.30	79.48	87.46	59.97	69.90	80.94	56.15	67.16	80.27
Mn (Manganese)	µg/L	368.82	391.24	415.29	443.79	629.74	863.60	479.48	680.90	879.24	566.56	738.17	926.77	606.98	780.59	967.30
Na (Sodium)	mg/L	70.29	70.79	71.21	98.66	105.50	113.19	77.40	82.25	88.54	48.25	52.38	56.67	37.69	41.79	45.89
Ni (Nickel)	µg/L	8.24	12.42	20.47	207.82	425.49	892.65	145.26	298.76	554.66	81.94	159.78	307.83	65.08	131.64	265.52
Pb (Lead)	µg/L	1.74	1.89	2.11	51.45	54.69	57.77	19.88	21.81	24.31	22.35	24.95	27.82	21.31	24.44	27.95
Sb (Antimony)	µg/L	0.67	0.71	0.74	13.60	16.34	19.03	9.55	10.63	11.85	6.15	6.78	7.60	5.28	5.89	6.66
Se (Selenium)	µg/L	0.76	0.77	0.78	3.92	4.82	5.75	2.66	3.15	3.75	1.59	1.83	2.13	1.33	1.55	1.82
SO4 (Sulfate)	mg/L	335.79	338.29	340.16	342.74	377.24	423.79	261.86	286.99	318.32	160.27	182.14	201.98	135.14	155.73	176.56
Tl (Thallium)	µg/L	0.18	0.18	0.18	0.19	0.19	0.19	0.17	0.18	0.18	0.15	0.16	0.17	0.15	0.16	0.17
V (Vanadium)	µg/L	4.36	4.42	4.52	9.35	9.45	9.54	8.49	8.67	8.85	7.33	7.61	7.90	7.37	7.63	7.90
Zn (Zinc)	µg/L	14.53	15.01	15.74	129.04	160.40	257.26	122.12	141.34	170.87	67.95	81.14	129.31	47.00	57.68	104.92

(1) Values shown are the average of the monthly P10, P50, and P90 values, as indicated, for the referenced Mine Year; see Section 6.4 of Reference (2).

DRAINAGE FROM COPPER-NICKEL TAILINGS: SUMMARY OF A THREE-YEAR FIELD STUDY

July 2004

Minnesota Department of Natural Resources
Division of Lands and Minerals
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In 1976, AMAX began the construction of an exploratory test shaft at its project site located about four miles southwest of Babbitt, MN. (Figure 1) The primary purpose of the project was to gain information on the grade and continuity of the deposit and collect a bulk sample for processing studies. However, AMAX also committed to conducting environmental studies on mine waste weathering that would provide information for an Environmental Impact Statement, if the project were to move ahead. Six test piles of rock from the shaft and associated drifts were constructed to measure water quality and quantity and the effect of reclamation on these values. Data from these studies have been summarized in a variety of DNR reports (Eger and Lapakko, 1985, Lapakko, 1993, and Lapakko et. al. 2004). In addition to the studies on waste rock, a small plot with tailings from the project was constructed in 1978. This plot was designed to not only provide data on water quality but also to be used for vegetation studies. The results of the vegetation work have been summarized in a report prepared by Barr Engineering (Borovsky, 1983). This report summarizes the water quality collected from the plot by the Minnesota Department of Natural Resources over the period 1979-1981.

OBJECTIVE

Determine water quality and flow from copper-nickel tailings.

METHODS

Experimental design

In November 1978, a tailings plot approximately 20’ x 30’ x 2’ deep, denoted FL7, was constructed. (Figures 2, 3) A 30-mil Hypalon synthetic liner was placed beneath the tailings to prevent seepage and provide an impermeable base for a drainage collection system. The tailings were placed on top of the liner and final grading was done using hand tools to smooth the surface and provide a depth of approximately 50 cm. A slight crown was maintained on the tailing surface to ensure adequate surface drainage.

The liner was sloped to a 6 inch PVC perforated pipe that was installed on the down slope end of the plot to collect leachate. The leachate was collected in the pipe and flowed into a sump. The leachate was pumped through a flow meter to record total flow, and a Rustrak event recorder (Model 292-4) was used to more precisely register the timing of the flow. For each pump cycle a fixed volume of sample was pumped into a plastic composite container for water quality analyses (Figure 4).

In the initial phase of the study, the total amount of flow recovered was lower than expected and it was believed that fine material had clogged the drainage collection pipe.

In August 1979, the collection pipe was excavated and the pipe was wrapped in a nylon mesh screen and turned so the perforations faced downward.

Tailings

The tailings were processed by the Twin Cities Research Center of the U.S. Bureau of Mines from crude ore samples collected from the Duluth Complex formation at the Minnamax site (Schluter and Mahan 1981). The tailings were processed using a bulk flotation process. Sodium isopropyl xanthate and MIBC (methyl isobutyl carbonol) were used in the flotation circuit, as a collector and a frother, respectively. An unspecified conditioner was also added to the circuit.

Tailings Analyses

Soil Fertility Analyses

General soil properties and extractable metals were analyzed by Borovsky et al. 1983. The following methods were taken from that report.

Ten random samples were selected from the bulk sample. All samples were air dried, crushed and passed through a 2 mm sieve. Chemical and physical properties of the tailing were expressed as calculated on the less than 2 mm fraction. Particle size analysis for sand, silt and clay was conducted by the standard hydrometer method (Day 1965) and content of very fine sand was estimated by use of the wet sieve procedure (Day 1965). Water capacity was determined by the pressure cell method (Klute 1965). Organic matter in the tailings was estimated by loss on ignition at 500^{o} C. Soil pH and soluble salts were measured electrometrically in water (1:1 dilution) as described by Peech 1965 and Bower and Wilcox 1965. Available phosphorus and potassium were determined as phosphorus and potassium soluble in dilute acid-fluoride (Olsen and Dean 1965). Exchangeable potassium, sodium, calcium, and magnesium were extracted in neutral 1N ammonium acetate (Pratt 1965a: Pratt 1965b: Heald 1965). Exchange acidity was determined according to Yuan (1959) and the sum of exchangeable bases and exchange acidity was used to estimate the cation exchange capacity. The concentration of extractable metals (Cu, Zn, Ni, Co, Cd, Mn, Pb, Cr, Fe, K, Ca, Mg, and Na) in the tailing was determined by shaking 3 grams of tailing in 15 ml of 1N nitric acid for 24 hours, filtering, diluting to 100 ml volume with distilled water and analyzing by flame atomic absorption (Table 1).

Total chemical analyses

Additional analyses were conducted on a split of the bulk sample that was used in the joint disposal experiment conducted by the MN DNR (Eger et al, 1984, Lapakko et al. 1985). The tailings were analyzed for Cu, Ni, Co, and Zn at the MN DNR lab in Hibbing, MN (Table 2). The sample was crushed using a Davis pulverizer to less than 0.15 mm. A 0.10 g sample was digested in 3.5 ml HCL, 2 ml HNO_3 and 1.5 ml HF in a Parr digestion bomb at 100^{o} C for one hour. The sample was brought up to a volume of 100 ml, and analyzed in flame mode on a Perkin-Elmer 603AA spectrophotometer (Farrell et al. 1981).

Total sulfur was analyzed by Lerch Brothers Inc. in Hibbing, MN. The sample was crushed using a Davis pulverizer to less than 0.15 mm, the sulfate sulfur was extracted with
dilute HCL, and the solid sample was then analyzed by dry combustion on a Leco combustion furnace. The sulfur remaining after sulfate extraction was assumed to be in sulfide form (ASTM 1983) (Table 2).

Saturated hydraulic conductivity was determined at the Minnesota Department of Transportation, St. Paul, using the falling head permeameter method (Klute 1965). For determination of specific surface area a 1.5 to 3.0 g sample was placed in a sample holder, out gassed and run on Quantasorb: three-point BET method used with relative N_2 pressures of 0.1, 0.2 and 0.3 at the MN DNR lab (Quantachrome Corp. 1981) (Table 2).

The mineralogy of the tailings was not analyzed, but it would be expected to be similar to that of the initial ore. The ore was approximately 40 to 70 percent plagioclase, with about 15 to 40 percent combined olivine, pyroxene and amphibole (Stevenson et al. 1979). Chlorite, biotite and smectite have each been found in ore at levels less than 5 percent (Stevenson et al. 1979). Some of the trace metals in the Duluth Complex do not occur as discrete metal sulfides, but are included within olivine, pyroxene and plagioclase (Iwasaki et al. 1982).

Water Quality Analyses

Water samples were analyzed for specific conductance, pH, alkalinity, and metals at the MN DNR laboratory. Specific conductance was analyzed using a Myron L conductivity meter, and an Orion 601A equipped with a model 9104 electrode, or a Radiometer Copenhagen 29 meter, equipped with a combination pH electrode, was used for pH analyses. Alkalinity was determined using standard titration techniques for an endpoint of 4.5 (APHA et al. 1976).

Samples for filtered metals (Cu, Ni, Co, Zn) were filtered through a 0.45 m filter, acidified with 0.1 ml concentrated ultra pure HNO_3 per 100 ml sample, and refrigerated at 5^{o}C. Analyses were conducted in flame or furnace mode using a Perkin-Elmer 603AA spectrophotometer. Samples for total metals (Ca, Mg, Na, K, Fe, Mn) were acidified with 0.1 ml concentrated ultra pure HNO_3 per 100 ml sample and refrigerated at 5^{o}C. An aliquot of one to five ml was placed in a flask with 10 ml 50,000 mg/L $LaCl_3$ and brought up to 100 ml. Analyses were in the flame mode on a Perkin-Elmer 603AA spectrophotometer.

Sulfate and chloride were analyzed at Serco Laboratories in Roseville, MN using the barium sulfate turbidometric technique and titrimetric mercuric nitrate technique, respectively. Dissolved organic carbon was analyzed at the Minnesota Department of Health laboratory in Minneapolis, MN, (See Table 3 for drainage quality data).

RESULTS

Precipitation

Precipitation from 1979 to 1981 was 63.3, 58.8, and 63.4 cm, respectively, approximately 10-20% below average. Precipitation for July 1981 through September was extremely low, roughly 50% of normal (Table 4).

Flow

Flow data were available from 1979 through 1981. Total flow volumes were recorded each time a sample was collected and combined to give a measure of the total average annual flow. Flow increased with time, with very low values recorded in 1979 (1055 liters), to 4600 liters in 1980 and the largest annual volume (14,865 liters) was recorded in 1981. In 1981 about 34% of the input precipitation was measured as outflow, and about 60% of the total flow occurred from February through April (Table 5).

Water Quality

pH

The pH of the drainage was generally above 7, with most values above 7.5 (Figure 1) Average annual pH ranged from 7.3 to 7.8, with no obvious trend with time. The pH did drop below 7 during spring melt in 1981.

Major cations and anions

All major cations, chloride and sulfate were elevated in the drainage, with the maximum average concentrations recorded in 1980. Sodium was the dominant cation at 880 mg/l, while Cl was at 1940 mg/l and sulfate at about 2400 mg/l. Concentrations of chloride and sulfate were 1940 mg/L and 2400 mg/L, respectively.

Specific conductance, which is a measure of the total dissolved solids, was at its highest values in 1980, and reached a maximum of about 15,300 umhos/cm^2 in October of that year. Values generally decreased during spring runoff and were particularly low during the heavy melt in the spring of 1981 (Figures 2 and 3).

Trace Metals

Nickel was the major trace metal in the drainage with concentration s ranging from 0.020 mg/l during spring runoff to 0.43 in the fall of 1980. Concentrations of other trace metals were about 10 to 20 percent of nickel concentrations. Concentrations of all metals generally followed similar trends with lower concentrations during spring melt (Figure 4). There were no obvious trends with time over the short time span of this experiment (See Tables 6 and 7 for mean annual concentrations and summary statistics).

DISCUSSION

When the tailings in this study were produced, a selective flotation process was used. Iron sulfides were suppressed in an attempt to recover only sulfides that contained the trace metals of interest. As a result, the majority of iron sulfides in the ore remained in the tailings. These iron sulfides are unstable in the presence of oxygen and release acid and sulfate to solution. At some mines, all the sulfides are floated, thereby reducing the residual sulfide content of the tailings and reducing the overall environmental risk.

The total sulfide concentration in the tailings was 0.38 % and pH remained above 7 for the course of the study. Based on laboratory testing with Duluth Complex waste rock, acid drainage could occur at total sulfur contents of 0.2 to 0.4% (MN DNR 2004). Some of these samples produced circumneutral drainage for 14 years then acidified. Consequently, the comparatively short three-year field study is inadequate to determine if the tailings would generate acidic drainage. A laboratory study is presently in progress to examine long-term dissolution of Teck Cominco's pilot plant tailings. These tailings have a sulfur content of 0.2% (Table 8).

Even though the tailings did not produce acid, low levels of trace metals, particularly nickel were released to solution. Although the concentrations observed in this study were not acutely toxic, levels may exceed chronic toxicity values. Both acute and chronic toxicity are a function of solution hardness. MPCA water quality rules provides a series of equations to calculate toxic levels for individual metals as a function of hardness.

Trace metal concentrations measured in this study were about one-third of those measured by Borovsky in his gravitational samplers (Borovsky 1983). One of the problems with this particular plot was that water did not infiltrate uniformly through the tailings. Some water would move across the surface and infiltrate at the low point of the plot immediately above the collecting pipe. This would result in a shorter contact time and could lead to lower concentrations.

This plot models tailings in an unlined tailings basin, similar to a taconite tailings basin, or the beach area of a lined basin. Currently the most widely accepted management practice for sulfide containing tailings is to maintain them in a submerged condition. Canadian mining operations generally maintain a minimum of a 1 meter water cover over the tailings to restrict oxygen transport and subsequent oxidation of the tailings. Covering acid generating tailings with a saturated substrate or water has prevented acidification but some trace metal release still occurs (Eger et al., 2000)

Drainage from this plot also contained elevated chloride and sulfate concentrations. Sulfate is generally produced from the oxidation of sulfide minerals present in the tailings, but the source of chloride is not known. Chloride concentrations in the Duluth complex are very low, and the chloride may have been added during the processing or there may have been some contamination of the tailings during the storage at the U S Bureau of Mines.

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Table 1. Average chemical and physical characteristics of copper-nickel tailing (± standard error)[1]. Results are from Borovsky et al. 1983.

Tailing Property	Copper-Nickel Tailing Amax
Bray phosphorus, g/g	0.50 ± 0.0
Exchangeable cations, meq/100g	
Calcium	1.80 ± 0.02
Magnesium	1.30 ± 0.05
Potassium	0.22 ± 0.004
Sodium	0.72 ± 0.02
Acidity	0.042 ± 0.002
Cation exchange capacity, meq/100g	4.08 ± 0.06
pH (H_2O), unitless	6.9 ± 0.03
pH ($CaCl_2$), unitless	6.1 ± 0.06
Conductivity, mmhos/cm	8.8 ± 0.7[2]
Extractable metals, g/g	
Cadmium	Trace
Chromium	5.3 ± 0.2
Copper	103.8 ± 2.4
Nickel	147.6 ± 2.8
Lead	24.1 ± 2.5
Zinc	38.2 ± 0.8
Cobalt	34.5 ± 0.6
Manganese	243 ± 30
Iron	25931 ± 530
Magnesium	13299 ± 249
Calcium	1353 ± 69
Sodium	340 ± 10
Potassium	322 ± 7
Particle size, weight pct:	
Sand (2.00-0.05 mm)	53.1 ± 0.5
Silt (0.05-0.002 mm)	42.0 ± 0.5
Clay (<0.002mm)	4.9 ± 0.5
Very fine sand (0.1-0.05 mm)	10.4 ± 1.2
Moisture content, weight pct at:	
0 MPa	57.0 ± 5.6[2]
-0.01 MPa	24.3 ± 5.0[2]
-0.033 MPa	22.4 ± 4.6[2]
-1.50 MPa	0.1[3]

[1]Based on 10 replications.
[2]Based on 3 replications.
[3]Extrapolation based on 21 observations between 0 and –1.5 MPa.

Table 2. Trace element content, saturated hydraulic conductivity, and specific surface area of tailings. Analyses were on Duluth Complex tailings used in an unrelated experiment (Lapakko et al. 1985).

Total Element Content mg/kg [1]					Saturated Hydraulic Conductivity			Specific Surface Area m^2/g
Sulfur	Copper	Nickel	Cobalt	Zinc	Packed Bulk Density (g/cm^3)	Estimated [2] Porosity (percent)	Hydraulic Conductivity cm/sec	1.6 [3]
3,800	420	350	110	180	1.55	47	1.6×10^{-4}	
					1.85	37	4.71×10^{-5}	

1 – Data reported on less than 2 mm diameter size fraction on an air-dry basis.

2 – Material density of 2.94 g/cm^3 for tailings was assumed.

3 – Mean of two values.

Table 3. Copper Nickel Tailings Drainage Quality Data 1979-1981 (concentrations in mg/L unless otherwise indicated)

Date	Alk	pH	Temp C	SC (umhos/cm)	Ca	Mg	Na	K	Cu	Ni	Co	Zn	Fe	Mn	SO4	Cl	DOC	Volume (liters)
3/23/79					430.0	505.0	1220.0	52.0	0.070	0.330	0.070	0.020	0.050	0.240	2750.0	2410.0		30.0
6/7/79		7.8		3377	276.1	147.0	219.5	37.4	0.040	0.125	0.013	0.020	0.020	0.070				60.6
6/8/79	108	8.3	23	6696	426.8	312.0	405.0	82.8	0.059	0.200	0.030	*0.68	0.060	0.130	2100.0	1230.0		18.9
6/22/79	97	7.9	19	3477	306.0	158.0	350.0	30.0	0.020	0.130	0.008	0.010	0.020	0.070	1220.0	513.0	6.3	22.7
9/1/79			14	1297	231.2	51.6	39.2	17.2	0.030	0.100	0.004	0.010	0.020	0.040	1400.0	446.0	12.0	11.4
9/10/79	20	7.4	11	1773	306.0	79.6	94.8	22.6	0.030	0.070	0.000	0.010	0.050	0.020	1150.0	116.0	5.3	75.7
9/12/79	43.2	7.7	20	3225	446.8	152.6	229.6	41.0	0.030	0.110	0.008	0.010	0.020	0.030	1700.0	310.0	6.8	83.3
9/13/79	43.2	7.9	8	3534	424.8	150.2	240.0	38.2	0.020	0.130	0.010	0.010	0.060	0.030	1700.0	330.0	7.0	22.7
11/2/79	49.6	7.5		4713	474.0	266.0	476.0	44.0	0.020	0.140	0.018	0.010	0.030	0.070			6.5	34.1
11/1/79	52.8	7.6		6596	498.0	396.0	740.0	53.2	0.040	0.180	0.060	0.020	0.030	0.020			8.9	53.0
3/31/80	8.05	6.6		435	38.0	10.4	14.4	2.6	0.020	0.020	0.010	0.010	0.020	0.010	120.0	33.0	1.0	49.2
4/2/80	12.6	7.0		475	44.0	11.2	17.0	2.6	0.020	0.020	0.010	0.010	0.020	0.010	150.0	48.0	1.0	37.9
4/7/80	12.6	7.0		900	105.0	22.8	38.6	5.8	0.020	0.020	0.020	0.010	0.020	0.020	380.0	76.0		367.2
4/17/80	20	7.0			219.0	85.0	137.0	16.4	0.020	0.040	0.020	0.010	0.020	0.020				359.6
7/7/80		6.4			141.0	45.0	77.0	8.8	0.034	0.014	0.014	0.020	0.050	0.110				11.4
9/4/80	60.4	7.4		8242	539.4	236.8	453.8	77.6	0.060	0.280	0.043	0.030	0.050	0.060	3220.0	2020.0	14.0	749.5
9/11/80	70	7.8		8584	600.0	788.0	1638.0	74.0	0.070	0.340	0.040	0.022	0.080	0.150	3780.0	1980.0		314.2
9/15/80	84	7.7	17	8132	486.8	270.2	475.2	73.2	0.080	0.280	0.020	0.029	0.040	0.240	3450.0	1700.0	13.0	541.3
9/24/80	90	7.8	18	8162	495.4	269.3	492.0	66.5	0.060	0.265	0.040	0.028	0.050	0.335	3290.0	1930.0		1230.0
10/9/80	90	7.9	18	11185	536.0	769.0	1758.0	84.6	0.100	0.350	0.040	0.020	0.040	0.580			16.0	13.0
10/13/80	79.1	7.5	10	15273	588.0	954.0	2208.0	102.2	0.100	0.430	0.060	0.020	0.040	0.770	1950.0	4690.0	19.0	15.0
10/24/80	98.6	7.6	12	9898.2	498.0	710.0	1638.0	72.8	0.070	0.300	0.040	0.020	0.030	0.600	3700.0	3390.0	15.0	412.6
11/10/80	96.9	7.7	15	13100	565.0	424.0	2500.0	72.0	0.090	0.350	0.060	0.030	0.060	0.920	3950.0	3490.0		177.9
2/19/81	11.9	6.5	10	88	3.9	2.3	2.6		0.040	0.010	0.010	0.020			12.0	8.0		553.0
2/20/81	14.4	6.8	13	90	6.5	2.3	3.3		0.020	0.020	0.010	0.010			12.0	8.0		401.0
3/24/81	12	6.5	15	40.8	5.2	2.5	2.6		0.040	0.010	0.010	0.010			8.0	7.0		848.0
3/25/81	17.6	6.3		90	7.8	2.6	6.5		0.100	0.010	0.010	0.010			14.0	5.0	18.0	886.0
3/28/81	29.6	6.5		320	27.3	7.9	2.6		0.170	0.030	0.010	0.020			68.0	18.0	35.0	1374.0
4/3/81	38.4	7.5		500	50.7	16.6	13.0		0.090	0.040	0.010	0.010						1317.0
4/13/81	26	6.9		3300	229.0	114.0	217.0		0.080	0.150	0.030	0.020			925.0	320.0		265.0

Table 3. Copper Nickel Tailings Drainage Quality Data 1979-1981 (concentrations in mg/L unless otherwise indicated)

Date	Alk	pH	Temp C	SC (umhos/cm)	Ca	Mg	Na	K	Cu	Ni	Co	Zn	So4	Cl	DOC	Volume (liters)
4/17/81	66.4	7.7			304.0	252.0	356.0		0.080	0.240	0.040	0.030			13.0	254.0
4/23/81	60.8	7.6		4300	222.0	165.0	279.0		0.070	0.140	0.030	0.020	1400.0	420.0		821.0
4/27/81	92	7.5		4175	255.0	170.0	264.0		0.070	0.130	0.050	0.010	1500.0	350.0		1287.0
4/28/81	72	7.6		2938	196.0	124.0	191.0		0.060	0.110	0.030	0.010	1125.0	240.0	8.8	1033.0
5/2/81	103	7.9		3750	350.0	198.0	276.0		0.050	0.160	0.040	0.020	1700.0	410.0		435.0
5/12/81	109	8.2	20	4950	430.0	350.0	428.0		0.050	0.220	0.060	0.020	2150.0	740.0	9.8	87.0
6/1/81	84	7.6	16	5862	500.0	400.0	530.0		0.090	0.290	0.070	0.030	2200.0	1000.0		76.0
6/2/81	94.5	7.6	17	4914	460.0	350.0	422.0		0.090	0.270	0.070	0.030	2200.0	720.0		219.0
6/6/81	106.4	7.9	19	6209	510.0	410.0	680.0		0.080	0.290	0.090	0.030	2550.0	995.0	9.9	269.0
6/22/81	129	7.5	18	4412	410.0	320.0	376.0		0.080	0.240	0.080	0.030	1910.0	609.0		965.0
6/24/81	140	7.6	18	4079	384.0	212.0	350.0		0.090	0.230	0.060	0.030	1840.0	540.0		859.0
6/28/81	113.6	7.4	16	2816	280.0	140.0	224.0		0.070	0.180	0.050	0.020			8.0	1321.0
6/30/81	121.9	8.3	25	3766	338.0	216.0	352.0		0.060	0.150	0.020	0.010				129.0
10/7/81	37.8	7.7		4700	474.0	218.0	260.0	40.0	0.050	0.180	0.060	0.020	2000.0	282.0		29.0
10/13/81	38.4	7.6		4850	450.0	216.0	264.0	38.0	0.040	0.200	0.040	0.030	1800.0	341.0	7.6	88.0
10/14/81	58	7.6		4300	392.0	212.0	264.0	38.0	0.040	0.210	0.040	0.030	1660.0	294.0	8.3	174.0
10/17/81	68.4	7.7		5000	398.0	262.0	414.0	40.0	0.050	0.240	0.050	0.030	2300.0	588.0		893.0
11/5/81	85.6	7.7		7190	436.0	510.0	794.0	48.0	0.070	0.300	0.050	0.010	3200.0	1200.0	12.0	325.0

*indicates an anomalous value

Table 4. Monthly and annual precipitation.

Month	Precipitation (cm)			
	1979	1980	1981	Average
January	1.30	2.44	1.24	1.66
February	4.85	1.68	3.40	3.31
March	6.98	2.31	1.88	3.72
April	2.50	1.90	11.20	5.20
May	9.73	1.32	2.46	4.50
June	10.10	9.09	15.50	11.56
July	7.04	6.27	4.29	5.87
August	5.89	13.40	4.39	7.89
September	5.08	10.80	5.97	7.28
October	7.59	3.66	9.55	6.93
November	1.40	2.84	1.60	1.95
December	0.89	3.10	2.01	2.00
TOTAL	63.3	58.8	63.4	61.8

Average data for Babbitt, from Hewitt, 1980

Table 5. Annual flow from tailings plot, FL7, 1979-1981.

Year	Total Annual Volume (liters)	Input		Yield [1] (%)
		Annual ppt (cm)	Total Volume (liters)	
1979	1,055	63.3	35,260	3.0
1980	4,640	68.8	32,750	14.2
1981	14,810	63.4	35,310	41.9

[1] yield = total annual volume outflow
Total water input (annual precipitation x plot area)

0.1 cm rainfall = 557 liters

Plot collecting area = 20’ x 30’ = 600 ft^2

Table 6. Water quality summary, average values, FL7 tailings plot, 1979-1981.

Parameter	1979	1980	1981	Average 1979-1981
PH	7.8	7.3	7.4	7.5
Alkalinity	59	60	69	63
Specific Conductance	3,850	7,670	3,440	4,987
Calcium	382	373	285	346
Magnesium	222	353	195	257
Sodium	401	880	279	520
Potassium	42	51	41	45
Chloride	765	1,936	433	1,045
Sulfate	1,720	2400	1,460	1,860
Copper	0.036	0.057	0.069	0.054
Nickel	0.15	0.21	0.16	0.17
Cobalt	0.022	0.032	0.041	0.032
Zinc	0.0133	0.020	0.020	0.018

pH reported in standard units

Specific conductance reported in mhos/cm

All other parameters reported in mg/L

Table 7. Summary statistics for copper nickel tailings drainage water quality

	Alk	*pH*	*Temp*	*SC*	*Ca*	*Mg*	*Na*	*K*	*Cu*	*Ni*	*Co*
Mean	65.15	7.5	16.2	4584	329.06	243.48	467.3	45.8	0.059	0.172	0.035
Standard Error	5.60	0.1	0.9	530	25.98	31.90	82.9	5.2	0.004	0.016	0.003
Median	67.40	7.6	17.0	4238	388.00	212.00	277.5	40.5	0.060	0.170	0.035
Mode	20.00	7.6	18.0	90	430.00	2.34	2.6	2.6	0.020	0.020	0.010
Standard Deviation	37.13	0.5	4.2	3514	180.01	221.02	574.3	27.3	0.030	0.112	0.023
Sample Variance	1378.81	0.2	17.7	12349529	32403.88	48848.27	329836.5	743.3	0.001	0.013	0.001
Kurtosis	-1.12	0.1	-0.1	1	-0.89	1.99	4.3	-0.8	2.209	-0.877	-0.792
Skewness	0.04	-0.9	-0.1	1	-0.54	1.39	2.1	0.1	0.937	0.141	0.429
Range	131.95	2.0	17.0	15232	596.10	951.66	2497.4	99.6	0.150	0.420	0.090
Minimum	8.05	6.3	8.0	41	3.90	2.34	2.6	2.6	0.020	0.010	0.000
Maximum	140.00	8.3	25.0	15273	600.00	954.00	2500.0	102.2	0.170	0.430	0.090
Sum	2866.75	343.0	372.0	201714	15794.70	11686.98	22432.7	1281.5	2.833	8.274	1.658
Count	44.00	46.0	23.0	44	48.00	48.00	48.0	28.0	48.000	48.000	48.000

	Zn	*Fe*	*Mn*	*SO4*	*Cl*	*DOC*
Mean	0.019	0.038	0.198	1752	890	10.9
Standard Error	0.001	0.004	0.055	187	178	1.4
Median	0.020	0.040	0.070	1750	433	9.4
Mode	0.010	0.020	0.020	1700	8	12.0
Standard Deviation	0.008	0.017	0.265	1152	1098	6.9
Sample Variance	0.000	0.000	0.070	1327152	1206272	47.7
Kurtosis	-1.469	-0.455	1.877	-1	3	5.6
Skewness	0.175	0.570	1.692	0	2	1.8
Range	0.020	0.060	0.910	3942	4685	34.0
Minimum	0.010	0.020	0.010	8	5	1.0
Maximum	0.030	0.080	0.920	3950	4690	35.0
Sum	0.889	0.880	4.545	66584	33807	262.2
Count	47	23	23	38	38	24

Table 8. Total tailings analyses.

Parameter	Amax Tailing FL7	Teck Cominco Tailing
S	0.38%	0.20%
Cu	420	508
Ni	350	366
Co	110	64
Zn	180	115

All trace metals values reported in mg/kg.

Figure 1. pH and alkalinity of drainage from FL7 tailings plot 1979-1981

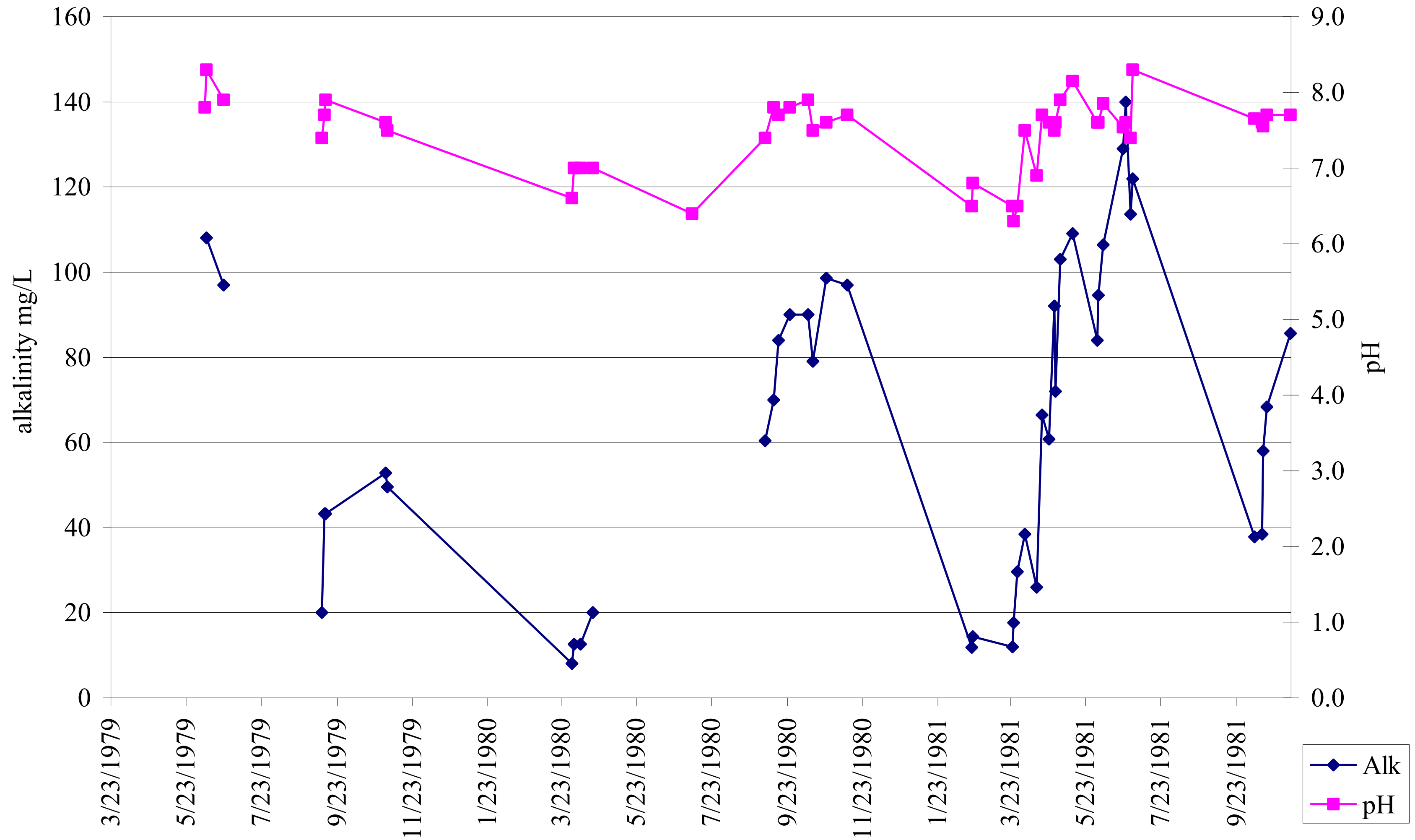


Figure 2. Ca and Mg concentrations in FL7 tailings drainage 1979-1981

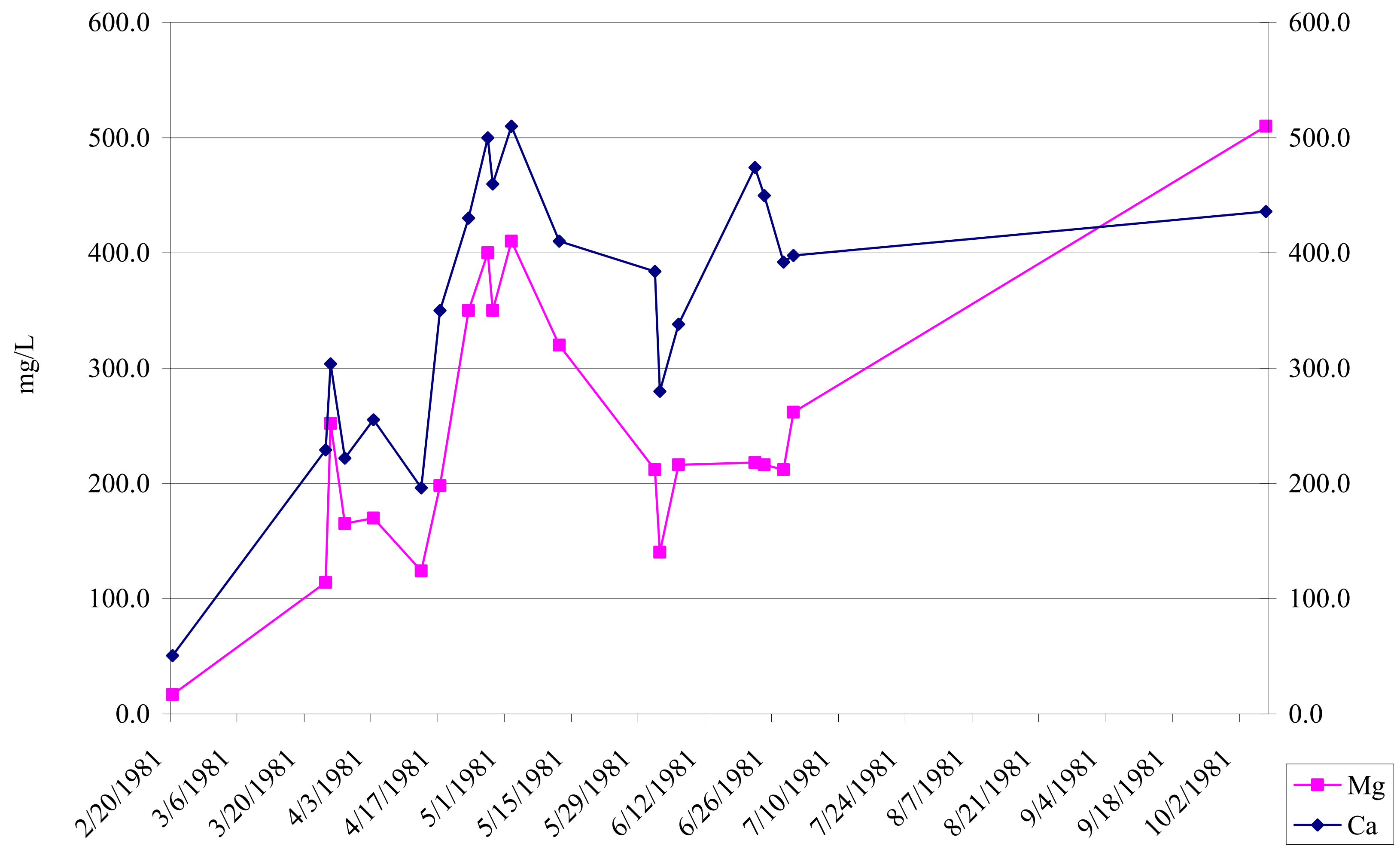
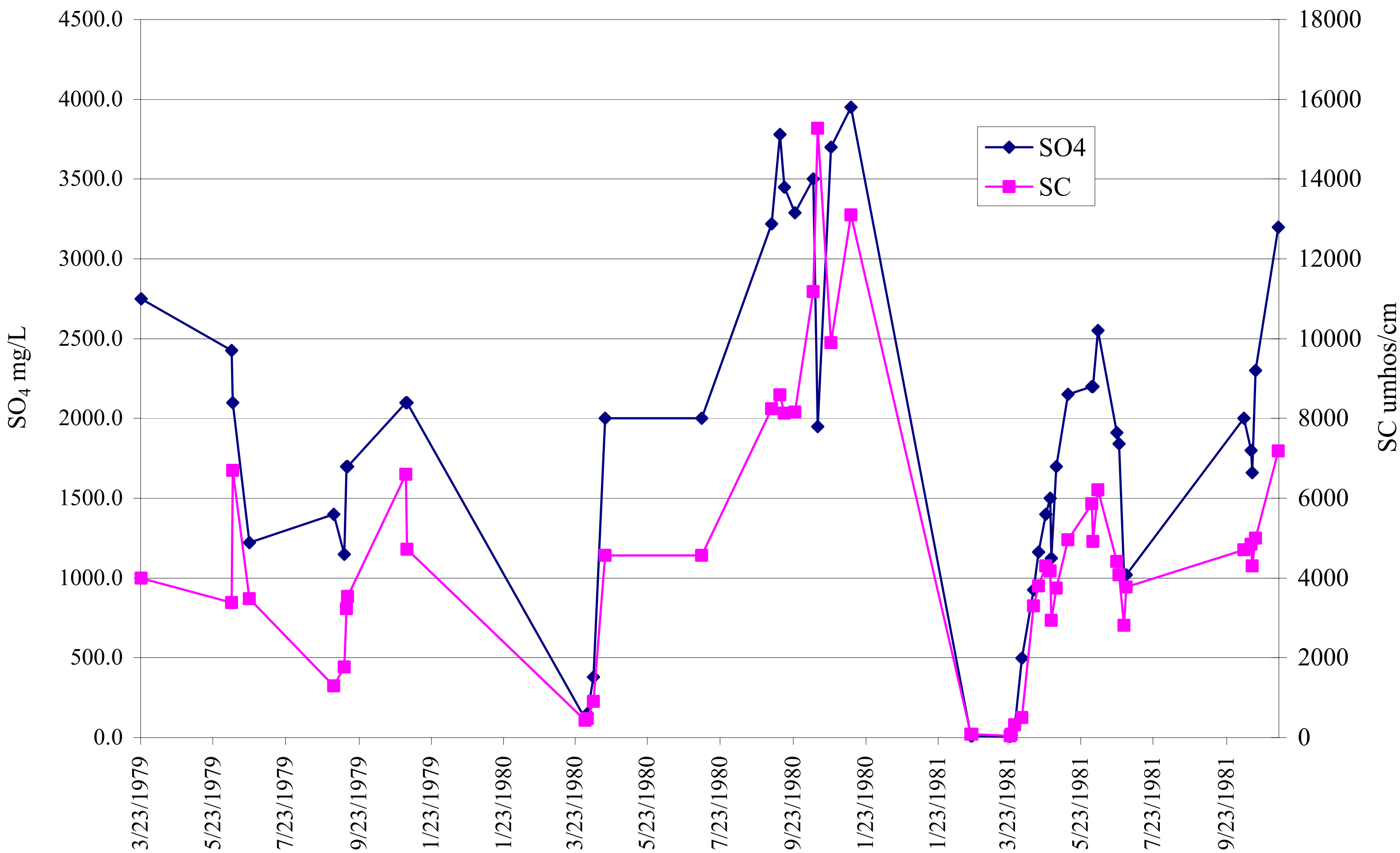


Figure 3. SO_4 concentrations and specific conductance (SC) of FL7 drainage 1979-1981



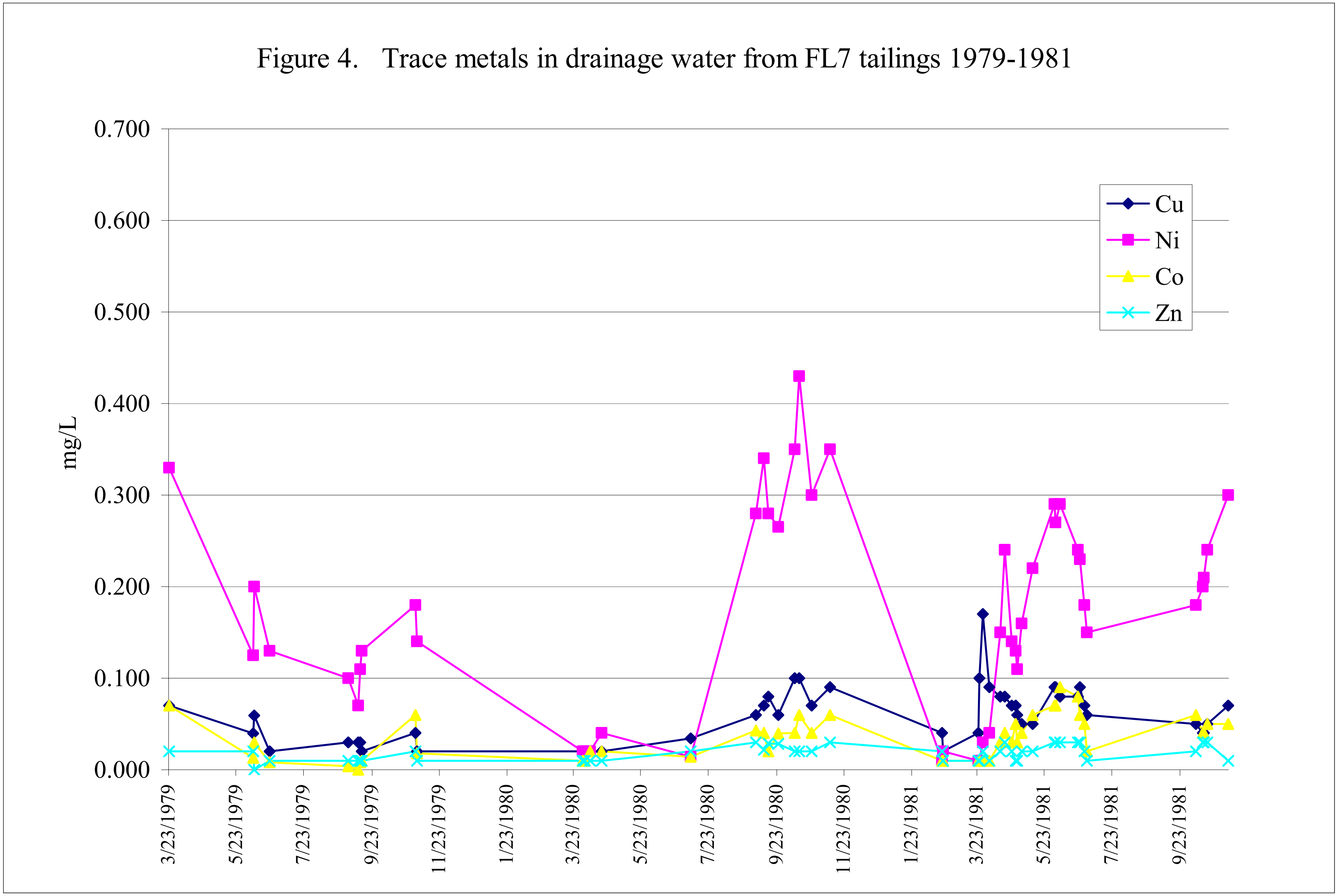
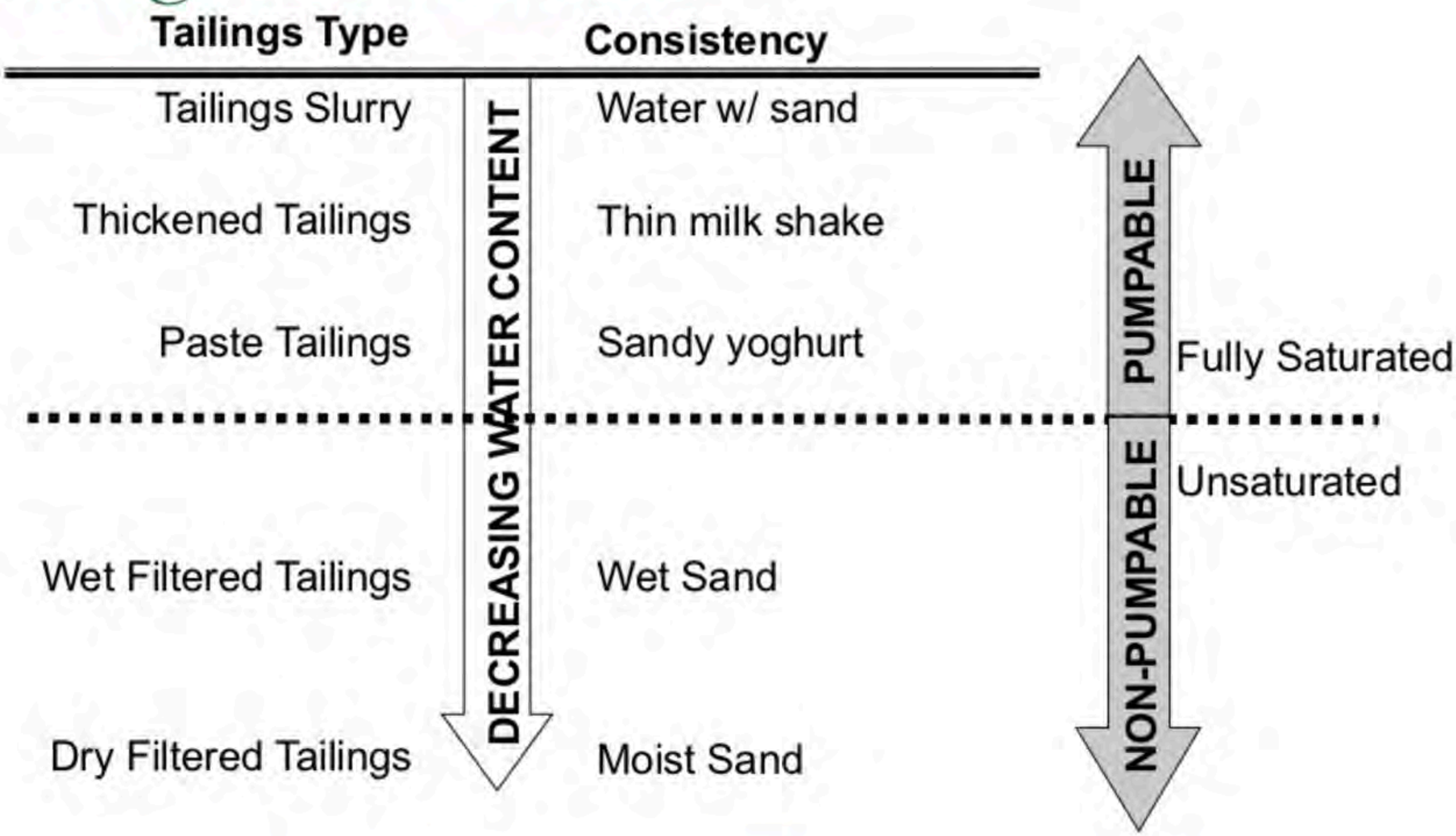


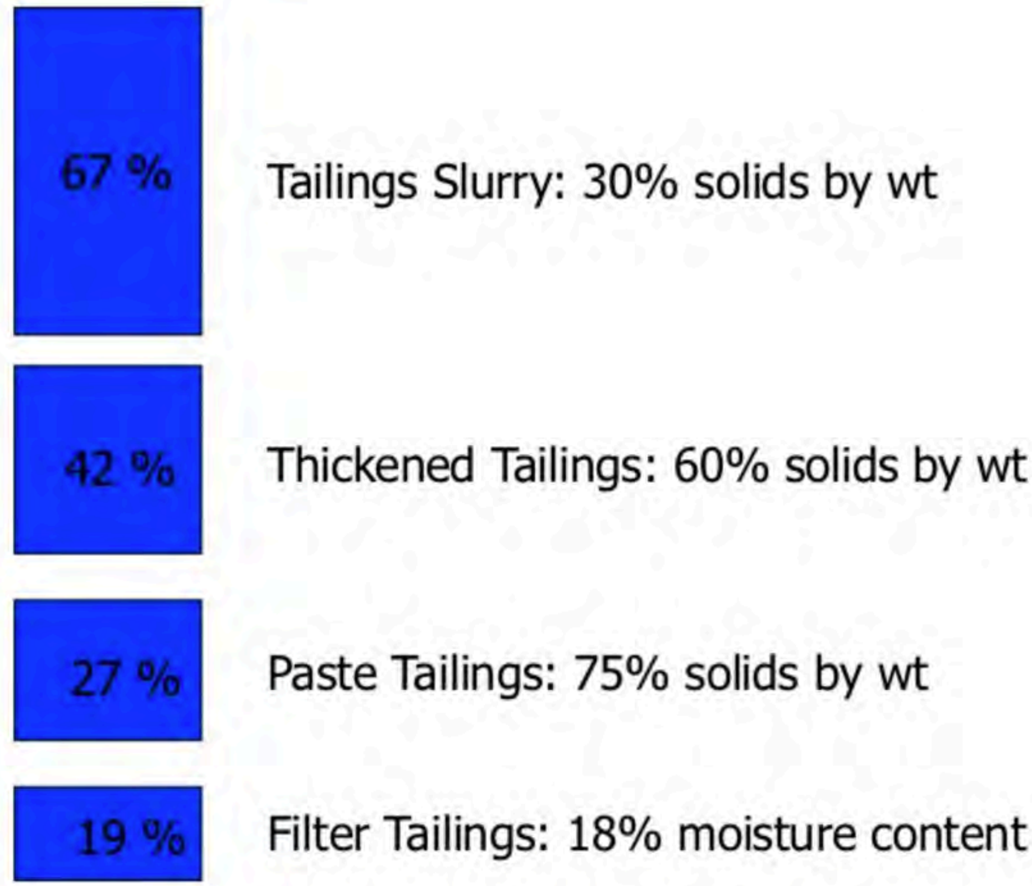
Figure 4. Trace metals in drainage water from FL7 tailings 1979-1981
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
mg/L
Cu
Ni
Co
Zn
3/23/1979
5/23/1979
7/23/1979
9/23/1979
11/23/1979
1/23/1980
3/23/1980
5/23/1980
7/23/1980
9/23/1980
11/23/1980
1/23/1981
3/23/1981
5/23/1981
7/23/1981
9/23/1981

http://www.slideshare.net/Rosemont-Copper/dry-stack-tailings-overview

Tailings Continuum



Tailings Percent Water



Tailings Slurry

- Least water conservative. Losses to:
  - Evaporation
  - Seepage
  - Lock-up (in tailings pore space)
- Seepage issues depending on water quality and impoundment design
- Water management (reclaim pool) critical to facility operation
- Most often lowest operating cost option

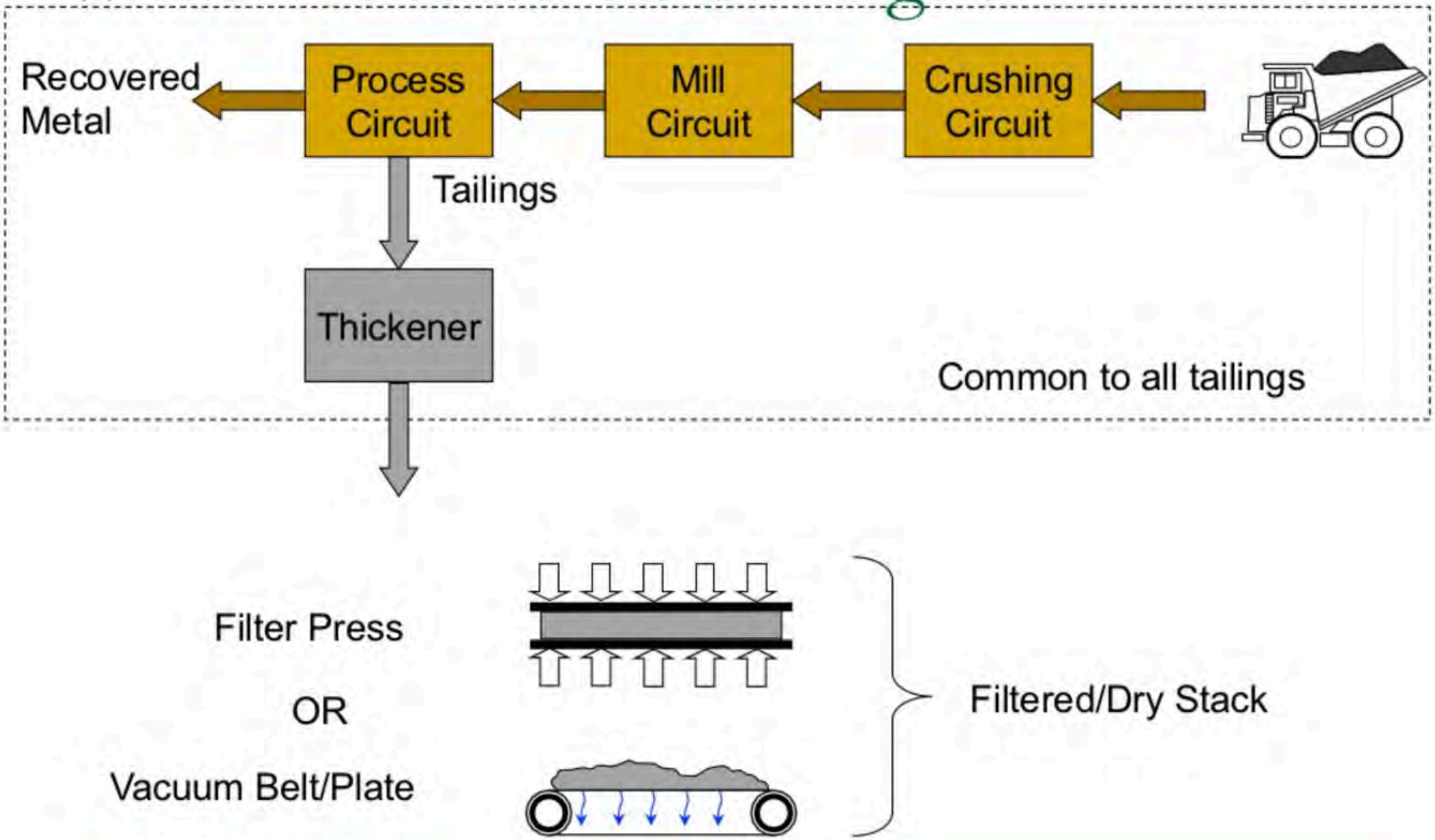
Tailings Slurry Design Considerations

- Containment dam:
  - Usually High Hazard
  - Impoundment of water pool
  - Piping concerns through dam
- Seepage management:
  - Underdrains
  - Cut-off walls
  - Pump back systems

Tailings Slurry Closure Considerations

- Closure challenges:
  - Concurrent reclamation difficult
  - Long-term consolidation settlements
  - Water management (seepage, consolidation, etc) continue during post-closure
  - Changing geochemical environment (saturated to unsaturated)

What Are Filtered Tailings ?



Filtered Tailings

- Most water conservative. Losses to:
  - Evaporation
  - Seepage
  - Lock-up (in tailings pore space)
- Seepage issues depending on water quality and impoundment design
- Moisture content and dust control critical to facility operation
- One of the highest operating cost option

Filtered Tailings Design Considerations

- Containment dam:
  - Low to Medium Hazard
  - Tailings stacked (+10% slope).
  - Tailings become construction material.
  - Stability of tailings stack. No liquefaction
- Seepage management:
  - Underdrains
  - Pump back systems

Filtered Tailings Closure Considerations

- Closure challenges:
  - Amenable to concurrent reclamation
  - No long-term consolidation settlements
  - Minimal water management during post-closure
  - No changing geochemical environment

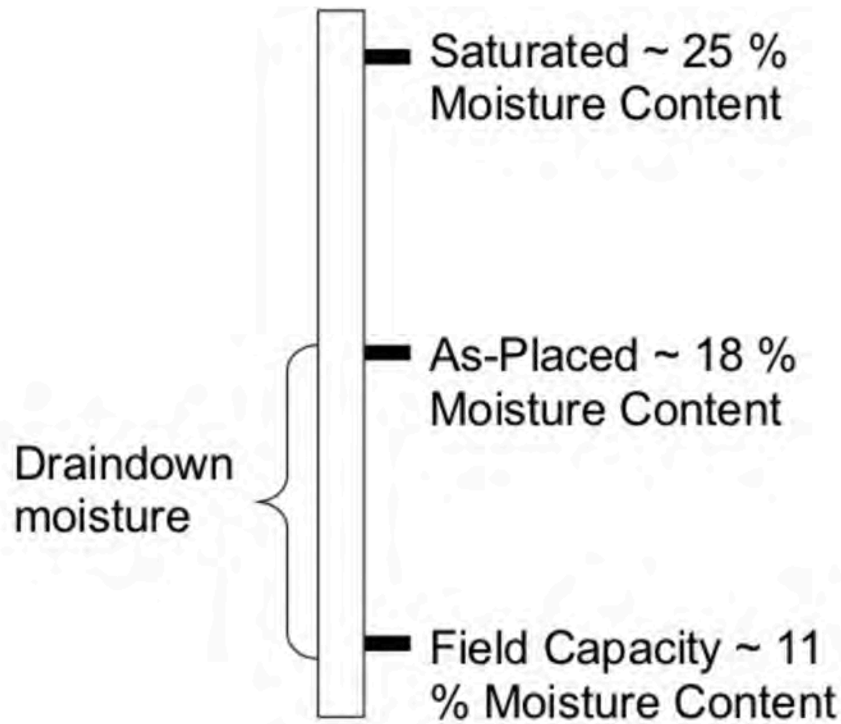
Filtered Tailings Benefits

Filtered Tailings

- Limited seepage compared to other tailings.
  - Rate
  - Quantity
- Material can be used as construction material
  - Compacted fill with high shear strength.
- Concurrent reclamation
- Surface water management
  - No water pool to manage
  - No chance of upset condition discharge

Filtered Tailings Seepage

- Seepage occurs as draindown from as-placed to field capacity moisture content.
- No water pool providing constant recharge (like slurry tailings)



LIMITED VOLUME OF SEEPAGE WATER

Seepage Rates

- Slurry tailings: 6.4 gpm/ac
- Paste/Thickened tailings: 0.06 gpm/ac
- Filtered tailings: 0.007 gpm/ac

TECHNICAL MEMORANDUM

Summary of Comments Resulting from Review of NorthMet Mining Project and Land Exchange Supplemental Draft Environmental Impact Statement

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1.0 BACKGROUND

This document is prepared to assist WaterLegacy in formulating meaningful comments on the PolyMet NorthMet SDEIS in a scientifically accurate manner. This memorandum focuses on issues pertaining to bedrock and surficial geology and the implications these subject areas have on groundwater flow and the possibility for interaction between groundwater occurring in surficial materials and groundwater within the bedrock.

A series of 16 individual PDF documents representing the entire SDEIS were downloaded from the Minnesota Department of Natural Resources ("MDNR") NorthMet Mining Project website. A 2-DVD set of supplemental reference materials dated November 2013 was provided by Bill Johnson at MDNR. These two sets of documents comprise the materials available for the purposes of this review. Because of the sheer volume of material contained in the SDEIS and the DVD set references - more than 64,000 pages – a complete and thorough review of all SDEIS materials was not possible considering time constraints. Rather, the sections of the SDEIS document itself dealing with geology were carefully reviewed, but only certain portions of the supporting reference materials could be reviewed in detail.

The subject of geology is of fundamental importance to any proposed mining project. For example, a thorough understanding of the mine site bedrock geology leads to models that accurately predict variations in ore grade and allow for the visualization of the complex three-dimensional structural relationships that exist between the various categories of ore and waste rock that that will be mined. During mining operations huge volumes of earth materials consisting of rock and overburden must be removed and transported efficiently and stockpiled without generating hazards such as instable slopes or impoundments, acid mine drainage and mobilization of toxic levels of metals. Bedrock and surficial sediments are the containers for groundwater and the

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platform upon which mine process waters interact with groundwater and surface waters such as streams, lakes and wetlands. Understanding the spatial variability of the various geologic materials and their degree of hydrologic interconnectivity are fundamental to understanding potential impacts to groundwater and surface water resources that result from mining.

There is considerable value in understanding the locations of highly permeable zones such as layers of unconsolidated sand and gravel, bedrock fault zones and other areas of fractured bedrock that have the potential to transmit groundwater at much higher velocities than surrounding materials. A confident understanding of the location of these potential groundwater conduits is required before effective engineering controls can be designed, constructed and operated to mitigate potential hazards. A mine plan based on sound geology leads to fewer operational problems as well as fewer negative environmental effects.

Lack of in-depth knowledge of mine site geology or a misunderstanding of certain aspects of mine site geology will have several negative effects. Some these negative effects create risks related to operations, for example unexpected variation in ore grade or issues with high wall safety, but they also include risks relating to the ability to accurately predict the environmental effects of a mining project. An overly simple or incorrect understanding of mine site geology greatly limits the ability to accurately predict the behavior of groundwater which gives rise to the inability to effectively design and construct engineered pollution mitigation measures and the inability to accurately forecast the financial resources necessary to operate them for the required length of time. Simply stated, geology forms the foundation that so many other aspects of the proposed NorthMet project are based upon. The geology presented in the SDEIS should be detailed, scientifically accurate, up-to-date and robust.

My first independent geologic field research was carried out in the vicinity of NorthMet 30 years ago. This field work was part of my graduate research that involved mapping the surficial geology of a portion of the eastern Mesabi Range area, including parts of the NorthMet Mining Project area. One additional aspect this research dealt with studying the relationships between bedrock type, bedrock structures such as faults and fractures and surficial landforms in northeastern Minnesota (Lehr, 2000). In the early 1990's I was co-organizer of a field conference held in the area of the eastern Mesabi Range and adjacent parts of the Superior National Forest that was attended by over 100 scientists from around the country. A synopsis of the surficial geology of northeastern Minnesota was published in a fieldtrip guidebook prepared for this field conference (Lehr and Hobbs, 1992). I have continued to map surficial geology across all of northeastern Minnesota, especially over the past few years since the release of high-resolution LiDAR data for these areas. A more complete summary of my qualifications to carry out this review are presented in my *Curriculum Vitae* attached at the end of this memo.

The comments below relating to those sections of the SDEIS that deal with geology are divided into five main sections by topic. The first section (2.0) covers the subject of bedrock fracturing at both the Mine Site and Tailings Basin Site and the implications bedrock fractures may have on groundwater flow. The second section (3.0) of this report contains a review of those sections of the SDEIS relating to surficial geology of both the Mine Site and Tailings Basin Site and its hydrologic significance. The third section (4.0) contains comments on bedrock geology that don't fit in the bedrock fracture section and the fourth section (5.0) contains a short discussion of the potential for hydrologic connections to exist between the surficial aquifer and the bedrock aquifer. The fifth section (6.0) contains additional comments that don't fit into any of the previous sections. Some concluding remarks are presented in section 7.0. A list of references cited is included in section 8.0. Two appendices are included with this report. Appendix A contains J.D. Lehr's CV and Appendix B contains certain figures referenced in this report.

2.0 BEDROCK FRACTURING

For projects such as the NorthMet Mine proposal a sound understanding the three dimensional geometry of bedrock fractures and their hydrogeologic properties will contribute to more accurate predictions of groundwater flow direction, flow rates and volumes. Prior to presenting a general discussion of bedrock fracturing below, a few technical terms used in the study of bedrock fractures are defined below.

> *"**Fracture**, a term from geology, refers to a surface along which a break has occurred in bedrock. An **open fracture** is a fracture with measureable distance (**aperture**) between sides of the fracture. A **fault** is a fracture along which there is displacement parallel to the fracture surface. Points originally adjacent on either side of the fracture are displaced. If there is no displacement between adjacent points on opposite sides of the fracture, the fracture is called a **joint**."* (Clark, *et al*, 1996, p. 2)

In general, the SDEIS gives only a cursory and simplistic treatment to the role bedrock fractures play in the transmission of groundwater at the NorthMet Mine Site and at the Tailings Basin. The entire treatment of bedrock fracturing at the Mine Site is presented on a single page (page 4-45). In many places within the SDEIS important statements made relating to bedrock fracturing are either unreferenced, inaccurately referenced or otherwise unsupported by data tables, figures or maps. Perhaps of greater concern are the numerous instances within the SDEIS where statements made related to the hydrologic significance of bedrock fractures blatantly misrepresent what the cited author(s) stated. Some of these particular instances will be highlighted below.

The simplistic approach the SDEIS takes in its treatment of the role of bedrock fractures in groundwater flow is underscored by Figure 3.2-28 of the SDEIS. This figure shows a conceptual cross section of the Tailings Basin, the geologic materials beneath and the groundwater containment system that is proposed to be constructed around its perimeter. This figure portrays the bedrock that occurs beneath the Tailings Basin as an *"assumed no-flow boundary"*. The implications of this are that groundwater flow through bedrock at the Tailings Basin is so insignificant that it can be conceptually ignored. If this assumption were accepted achieving the collection of 90 percent or more of contaminated groundwater would sound reasonable; however this rather critical hydrogeologic assumption is not supported by either data or cited references within the SDEIS.

Recent geologic mapping by the Minnesota Geological Survey shows a fault beneath the existing Tailings Basin and proposed Hydrometallurgical Residue Facility ("HRF") (Figure 1). Numerous other faults are mapped in close proximity (Jirsa *et al*, 2005; Jirsa *et al*, 2011; Jirsa et *al*, 2012). The hydrologic significance of these faults is unknown at this time because the SDEIS did not address them.

Numerous recently-developed tools and technologies are commonly used in combination with more traditional mapping methods to successfully evaluate the hydrologic properties of bedrock fractures. Evaluation of bedrock fractures and their hydrologic significance often begins with desktop research of linear trends that appear on imagery. The fairly recently released LiDAR topography datasets for northeastern Minnesota are a tremendously useful public-domain data source available for use during the initial phases of bedrock fracture studies. LiDAR data are especially useful in the densely forested areas such as northern Minnesota because topographic details beneath the pervasive cover of vegetation are revealed. The merging of LiDAR data with other datasets such as aeromagnetic data for example has proven useful in mapping bedrock fractures elsewhere (Golder Associates, 2010). Following up desktop research with traditional field mapping techniques further contributes to the understanding of bedrock fractures by recording the orientation of fractures traces at the land surface and the noting the character of the near-surface fracture surfaces and apertures.

In addition to traditional drill core logging, a number of borehole geophysical techniques can also be used to map bedrock fractures and characterize their hydrologic properties. These techniques include temperature logging, acoustic logging, resistivity, gamma and caliper logging and even optical (TV) logging of boreholes. A variety of traditional surface geophysical methods can also be employed to map and characterize bedrock fractures. These include ground penetrating radar, electrical resistivity and seismic surveys. Of course various borehole hydrologic procedures such as pump tests, packer tests, slug tests and tracer tests have direct application in the study of the hydrology of bedrock fractures (Golder Associates, 2010).

Apparently none of these techniques were employed in the SDEIS process to identify fractures or assess groundwater flow through fractured bedrock. This seems like a major omission, resulting in unsupported assumptions and inadequate information regarding groundwater flow at both the Mine Site and Tailings Basin.

2.1 Bedrock Fracturing – Mine Site

The rationale presented in the SDEIS in support of a rather simplified view of bedrock fracturing at the Mine Site begins at the top of page 4-45. Instead of describing the distribution of known fractures at the Mine Site and reporting on their hydrologic properties, this section instead uses anecdotal comparisons to downplay the significance of bedrock fractures at the Mine Site. The page leads off with the following three sentences.

> *"Concerns have been raised that fractures, including faults and fracture zones, may exist that could permit transmission of groundwater through the bedrock over distances of thousands of feet. Such features have been identified elsewhere on the Canadian Shield, but have been genetically associated with tectonic events occurring more than 1,600 million years ago (Farvolden et al. 1988; Douglas et al. 2000; Rouleau et al. 2003). These events would not be relevant to the Duluth Complex as they predate its emplacement during the formation of the Mid-Continent Rift approximately 1.1 billion years ago."* (SDEIS, p. 4-45)

This quote implies that the rocks of the Duluth Complex do not *"contain faults and fracture zones that could transmit ground water through bedrock over distances of thousands of feet"* because they are simply too young. Neither Farvolden *et al* (1988), Douglas *et al* (2000) or Rouleau *et al* (2003) make statements that support the SDEIS' assertion that the degree of faulting and fracturing of rocks is in any way related to the age of the rocks. On the contrary, one pertinent remark made by Farvolden el al (1988) is that *"mineral deposits on the Canadian Shield are commonly associated with geologic anomalies, in particular contact zones, <u>faults or fracture zones</u>"* (emphasis added).

The rocks of the Duluth Complex are indeed fractured and faulted. Faults are documented in several recently published geologic maps of the NorthMet property and surrounding areas (Severson and Miller, 1999; Miller and Severson, 2006a, 2006b, 2006c, 2006d; Jirsa *et al*, 2005; Jirsa *et al*, 2011; Jirsa *et al*, 2012) (Figure 1; Figure 2). This is also common knowledge amongst geologists working in the area. Even PolyMet's own geologists describe the rocks at the Mine Site as being fractured and faulted – they specifically mention 14 separate faults zones that transect the Mine Site (PolyMet, 2007b) (Figure 2). Some of the SDEIS' supporting literature also correctly characterizes the bedrock at the Mine Site as fractured in certain places. The presence of fractures in this part of the Duluth Complex has been known since the Copper-Nickel Study days. Siegel and Ericson (1980) reported that *"fractures and joints in the Duluth Complex may extend to considerable depths but are more extensive in the upper 200 to 300 feet of the bedrock"* (p. 7).

In certain places, the SDEIS acknowledges the presence of fractured bedrock at the Mine Site.

> *"The geologic and hydrogeologic settings of the Mine Site and the analog sites are fairly similar with a thin veneer of heterogeneous unconsolidated deposits underlain by fractured bedrock."* (SDEIS, p. 5-243)

> *"The hydrogeologic setting of the Partridge River watershed consists of a thin veneer of heterogeneous unconsolidated deposits (glacial till) underlain by fractured bedrock (Duluth Complex in most of the Mine Site and Virginia Formation in the northern portion of the Mine Site)."* (SDEIS, p. 4-149)

The SDEIS, in other places, acknowledges that groundwater flow through bedrock occurs through fractures or other secondary porosity features.

> *"The bedrock has low primary permeability, so groundwater flow within the bedrock is through fractures or other secondary porosity features."* (SDEIS, p. 4-149)

Yet, the SDEIS downplays the hydrologic significance of bedrock fractures and does not seem to include groundwater flow through fractures in its seepage calculations. Discussion of the hydrologic significance of bedrock fractures at the Mine Site continues on page 4-45 with the following quote:

> *"Foose and Cooper (1979; 1980) appear to have provided the only published work specifically looking at the presence of fracturing and faulting in the Duluth Complex. They identified numerous faults and fractures in their surface mapping of the Harris Lake area, as is commonly found in the surface exposures of crystalline bedrock. However, they described the most extensive faults—those most likely to be long distance groundwater conduits—as being largely filled with gouge. They also conclude that most of the faults and fractures formed early and at depth, during emplacement of the Duluth Complex, and were not related*

> *to post-emplacement deformation, which would have more likely resulted in fractures open to groundwater flow."* (SDEIS, p. 4-45)

First, there are no Foose and Cooper references listed in the SDEIS from either 1979 or 1980, so it is assumed the references and conclusions in this paragraph are from Foose and Cooper 1978 and 1981 which are cited in the list of references. Again, these statements made relating to bedrock fractures are not supported by the references cited in the SDEIS. Neither of the two Foose and Cooper papers report that *"the most extensive faults are largely filled with gouge*." Their only mention of fault gouge in these two papers is that they used its presence to trace fault zones in the field. Neither paper discusses distance groundwater may flow through faults and fractures in the Duluth Complex - in fact neither mention groundwater flow at all. The main purpose of Foose and Cooper's research was to demonstrate the usefulness of detailed mapping of igneous stratigraphy towards mapping fractures in what at first glance looks like entirely homogeneous rock.

The SDEIS uses Foose and Cooper's characterization of the faults in their study area as *"forming early and at depth"* as somehow contributing to lesser hydrologic significance than fractures that might have formed later or at shallower depths. However, no such claims are made in the Foose and Cooper papers and no data are presented to support this assertion in the SDEIS.

The sections of the SDEIS describing bedrock fractures rely mostly on references that are quite old while failing to reference vast amounts of more recent geologic data and scientific literature directly relevant to assess hydrologic role of bedrock fractures at NorthMet. PolyMet and its predecessors have acquired detailed site-specific knowledge of the geology of the NorthMet ore deposit. The NorthMet deposit mine plan and other critical documents and datasets, including all geologic data have been reviewed by what are essentially external auditors (AGP Mining Consultants Inc.) who prepared the 43-101 Technical Report for the NorthMet project (Desautels and Zurowski, 2012) on PolyMet's behalf. Quality geologic data have been collected over the years from the NorthMet area that could have been used to present a more detailed and realistic understanding of the bedrock fractures known to exist at both the Mine Site and the Tailings Basin than what is presented in the SDEIS.

One specific example of the type of data relevant to the nature of bedrock fracturing that have been collected but are not presented in the SDEIS is the RQD table from PolyMet's drilling database (PolyMet, 2007b). RQD is an acronym for "rock quality designator" and it represents a simple quantitative measure of the degree of rock fracturing that is calculated from basic measurements taken from drill core. Results of RQD calculations are reported as a percentage that ranges from 0 (more fractured) to 100 (less fractured). PolyMet reports the average of all RQD data for Duluth Complex rocks at NorthMet to be 93% (Desautels and Zurowski, 2012) to 94% (PolyMet, 2007b) - a number that by itself suggests relatively few fractures overall. However because it is an average, a certain portion of the RQD data would be less than 93 or 94%. Those cored intervals with RQD values less than 93% would indicate intervals that are more fractured than average – an important hydrogeologic characteristic to understand. More detail from the RQD table would allow for a greater understanding of the spatial variability of bedrock fractures.

Table 10-1 from Desautels and Zurowski (2012) below shows average RQD values from NorthMet broken down by rock unit. Note that units 1 to 7 are Duluth Complex rock units with unit 1 stratigraphically the lowermost and unit 7 the uppermost. The RQD values presented for each rock unit represent the average of a large number of individual RQD measurements. For example 4,194 individual RQD measurements were taken from drill core assigned to unit 1 to arrive at an average RQD of 91.8 for that unit.

Table 10-1: Summary of Core Recoveries and RQD Measurements (includes all drilling through summer 2007)

Unit	Recovery Count	Recovery Percentage (%)	RQD Count	RQD Percent
1	8,906	99.9	4,194	91.8
2	1,879	99.5	968	90.3
3	4,374	100	2,632	93.5
4	2,160	100	1,063	96.4
5	1,901	100	838	94.3
6	2,262	100	1,041	94.7
7	951	99.3	396	87.4
Virginia Formation	2,095	99.7	1,069	87.6
Inclusions	62	98.1	57	86.6
Biwabik Iron Formation	381	100	60	79.8
Duluth Complex Average		99.96		92.82

Table from (Desautels and Zurowski, 2012)

It is the lower RQD percentages in this dataset along with an understanding of their spatial distribution that would be particularly useful in predicting groundwater flow through bedrock. In other words, these RQD data may allow for more accurate mapping of fractures known to occur at the Mine Site and provide the ability to predict their range of hydrologic properties. It would be very instructive to view the spatial relationship between the lowest RQD values and fault zones and lineament trends mapped using LiDAR data.

Perhaps what is most obvious from Table 10-1 above is that overall the average RQD values for Duluth Complex rocks (93) are not that greatly different from the Virginia Formation (88) or even the Biwabik Iron Formation (80). Another important conclusion relating to bedrock fracturing can be drawn from examination of this summary of the RQD dataset. The RQD values of certain rock units within the Duluth Complex – unit 7 for example – have average RQD values less than or equal to the Virginia Formation (87.4 vs. 87.6). These data seem to contradict the numerous claims in the SDEIS that the degree of bedrock fracturing and therefore hydraulic conductivity values for the Duluth Complex rocks are so much lower than the extent of fracturing and resulting bulk hydraulic conductivities in the Virginia and Biwabik Iron Formations.

The discussion of bedrock fractures at the Mine Site and their hydrologic significance continues in paragraph 2 of page 4-45 with the following sentence.

> *"Evidence of several high-angle faults, consisting of brecciated intervals and fault gouge mineralization, was noted in the exploration cores from the NorthMet Project area (PolyMet 2007b)."* (SDEIS p. 4-45)

The statement above is accurate, but it omits important information about the dimensions of brecciated intervals and the orientation of the faults. This information would have a direct bearing on the potential for bedrock fractures to transmit significant quantities of contaminated groundwater. PolyMet's own geologic report states that *"fault zones are apparent in drill core and show up as brecciated intervals (<u>up to several feet thick</u>) including gouge mineralization (clay, calcite, quartz, etc.), slickensides on serpentinized fracture faces, and/or <u>severely broken</u> (<u>rubble</u>) <u>core</u>"* (PolyMet, 2007b, p. 16) (emphasis added). These specific details about the dimension of potentially very porous fault zones at NorthMet should be presented in the SDEIS and their hydrologic significance addressed in groundwater modelling where appropriate. The hydrologic implications of bedrock containing fault zones with field-documented dimensions on the order of several feet thick that are filled with rubbly rock at the Mine Site should have been specifically addressed in the SDEIS, but this analysis appears to be missing. These *"brecciated intervals several feet thick"* indicated by *"severely broken (rubble) core"* would have very low RQD values.

The high-angle orientation of the fault zones documented at the Mine Site also has specific hydrologic significance. Steeply dipping fractures are known to be very important for movement of contaminants to groundwater (Golder Associates, 2010). Additionally, it is virtually certain that the number of fractures documented from drill core greatly underrepresents the actual number of fractures present at the Mine Site. Because the faults mapped at NorthMet are high-angle faults (SDEIS, p. 4-45) and most of the exploratory bedrock drill holes at the NorthMet Mine Site were drilled vertically (PolyMet, 2007b), drill holes would not likely encounter fractures because of their high-angle orientation (Golder Associates, 2010).

The discussion surrounding recent tectonism within the Lake Superior region and the potential for those processes to affect groundwater flow through fractures is presented in the excerpt below from the SDEIS.

> *"There have been no other more recent tectonic events in the Lake Superior region that might have generated more recent fractures and faults or reactivated preexisting ones that would serve as significant zones of groundwater transmission."* (SDEIS, p. 4-45)

While there may not have been any major mountain-building events (tectonism) in northeastern Minnesota recently, it has been well known for decades that glacial isostasy causes fractures to form in crystalline rocks such as those present in Precambrian shield areas (Morner, 1978 for example).

Northeastern Minnesota has been entirely covered by continental-scale ice sheets on the order of dozens times over the past 2.5 million years or so. In response to the immense loads from these ice sheets, the earth's crust - including the entire Duluth Complex - was depressed, relative to its current attitude, on the order of several hundreds of feet during each glacial cycle. With each glacial cycle the downward forces due to the weight of the ice were of such magnitude that the viscous upper portions of the earth's mantle were actually displaced away from ice sheets during glacial maxima and then flowed back during interglacial episodes, allowing the crust beneath the former ice sheets to rebound upward. Episodic loading and unloading of the earth's crust that disrupts the geometry of the earth's mantle down to depths measured in miles is certainly capable of fracturing at least the upper several hundred feet of the earth's crust, especially in relatively brittle mafic intrusive rocks such as the Duluth Complex. Repeated flexing of the earth's crust and upper mantle to such a degree has most certainly caused relatively new bedrock fractures to form in the crystalline rocks of northeastern Minnesota and has also likely contributed to recent increases in aperture of older joints and faults. Incidentally, glacial isostatic rebound from the last glacial cycle that ended about 10,000 years ago is still under way in northeastern Minnesota, so the bedrock in the vicinity of the Mine Site has not yet reached isostatic equilibrium.

The discussion in the SDEIS relating to more recent faults and fractures does not take into consideration the significant and relatively recent large-amplitude crustal movements associated with glacial isostatic rebound and their fracture-generating and aperture-expanding potential. Extensive study surrounding the evaluation of crystalline rocks of the Canadian Shield as long-term nuclear waste repositories has resulted in a vast literature relating to bedrock fracturing and glacial isostatic rebound's effect on bedrock fracturing that may have applicability to the bedrock fracture situation at NorthMet (Trask *et al*, 1986 for example).

The SDEIS must recognize the fact that numerous faults and other fractures, including some that have recently formed, are documented at both the Mine Site and the Tailings Basin Site. The SDEIS must adjust the modeling of groundwater and contaminant flow accordingly.

Bedrock fractures frequently express their geometric patterns at the earth's surface even in areas where the bedrock has some thickness of sedimentary cover (Golder Associates, 2010; Morey, 1981). These types of patterns are referred to as **lineaments** (Clark, *et al*, 1996). The importance of lineaments to a sound understanding of groundwater flow through crystalline bedrock stems from a well-established relationship between lineaments and water-bearing features (Golder Associates, 2010). Lineament studies have been reported to be particularly useful in hydrologic studies of glacially stripped areas such as the Canadian Shield where the topography is controlled by the contrast between competent rock and weaker, linear fracture and fault zones (Golder Associates, 2010; Clark *et al*, 1996).

Lineaments in Duluth Complex rocks in the immediate NorthMet vicinity have been recognized as important to groundwater and contaminant flow for decades. Stark (1977) reported *"lineaments may overlie highly fractured rocks which could serve as channels for groundwater flow"* (p. 79) and that linear features may be optimal areas in which groundwater pollution hazards associated with copper-nickel development are greatest. Cooper (1974) demonstrated a close correspondence between joint spacing and proximity to lineaments in Duluth Complex rocks near NorthMet. Joint spacing in the Gabbro Lake area varied from one foot near lineaments to greater than 5 feet away from lineaments.

The more recent literature contains numerous specific examples of the direct correlation between lineaments expressed at the surface and water bearing zones in the subsurface. In one example, Mabee *et al* (2002) projected 38 surface lineaments into a 28 km long tunnel constructed through crystalline basement rock. Their data show a strong relationship between hydrologically significant fractures and surface lineaments. Of the 19 flowing zones in the tunnel, 13 coincided with the projection of surface lineaments into the subsurface. Additional significant findings of this study were that not all fractures in the tunnel had surface expression and that not all fractures present in the tunnel were hydrologically significant (Mabee *et al*, 2002).

The SDEIS presents a discussion of lineaments lower on page 4-45 that, contrary to current geologic literature, downplays the relationship of lineaments to bedrock fractures and therefore their significance to the hydrogeology of the NorthMet Site.

> *"Numerous lineaments have been mapped over northeastern Minnesota, but these have been associated with glacial deposition and not fracturing in the underlying bedrock (Morey 1981; Heutmaker and Morey 1982)."* (SDEIS, p. 4-45)

The cited literature refers to glacial "processes," not glacial "deposition" (Morey, 1981; Heutmaker and Morey, 1982). These terms do not have the same meaning. Glacial processes include glacial erosion as well as glacial deposition. It is widely known that glacial erosion of crystalline bedrock across large areas of northeastern Minnesota and other parts of the Canadian Shield has resulted in lineaments that reflect bedrock discontinuities such as faults and joints. This is supported by Morey's (1981) own statement that *"there is a striking correspondence between the lineaments and bedrock structures where the structures are known in the ice-scoured areas covered by only a thin veneer of ground moraine."* Other published literature has documented surface topographic expression of bedrock fractures in many areas of the eastern Mesabi Range (Cooper, 1974; Stark, 1977; Morey, 1981; Heutmaker and Morey, 1982; Lehr and Hobbs, 1992; Lehr, 2000).

My own mapping of surficial geology in northeastern Minnesota, both published and unpublished, provides numerous examples where subglacial melt waters exploited bedrock lineaments as evidenced by the numerous eskers that were deposited in such landscape positions. Prior to the glacial hydrologic conditions that led to the deposition of eskers in these locations, subglacial melt waters would at times have been under extreme and highly variable pressures, especially during the sudden drainage of ice marginal lakes (Sharpe and Cowan, 1990). These high pressure subglacial melt waters would have had tremendous erosive power and would have been very effective at accentuating the topographic trends of bedrock joints and faults (lineaments) by eroding near-surface fracture-fillings and otherwise having relatively little erosive effect on sound crystalline rock between fractures. High-pressure subglacial melt waters were likely quite effective at expanding the aperture of near-surface fractures in the Duluth Complex and adjacent rock units.

The argument is then made in this section of the SDEIS that since over-pressured groundwater was not encountered at NorthMet, hydrologically interconnected bedrock joints or faults do not exist at NorthMet. This rationale would ignore the simpler and well-known hydrologic situation where hydrologically interconnected bedrock fractures exist under water table conditions (Siegel and Ericson, 1980), not over-pressurized conditions. The SDEIS reads:

> *"One exploration borehole at the Minnamax prospect encountered groundwater at a depth of 1,390 ft in the Duluth Complex that flowed for a period of 6 days, indicating the potential presence of over-pressured groundwater in the bedrock (Barr 1976). However, none of the other 12 exploration borings completed on the prospect encountered similar conditions,*

> *indicating little to no hydrogeological interconnection of bedrock fracture or fault zones across the area of that prospect. No similar conditions of over-pressured groundwater flow were encountered in any of the exploration boreholes or other boreholes completed at the NorthMet Project area. Extensive, long-distance groundwater flow through shallow weathered and fractured bedrock is likely limited by glacial scouring and removal of the highly weathered and fractured upper zone of bedrock commonly observed in crystalline bedrock elsewhere in the world."* (SDEIS, p. 4-45)

The argument that since exploration boreholes did not encounter over-pressurized groundwater, there is little or no hydrogeological interconnection of bedrock fracture or fault zones, is spurious. The purpose of drilling at Minnamax and NorthMet was mineral exploration/deposit evaluation. Because diamond core drilling has always been costly, drilling programs evaluating ore deposits such as NorthMet (deposits where mineralization is not restricted to fracture zones) attempt to site their drill holes in areas where they believe there to be sound rock, not fractured rock.

One of the primary objectives of mineral exploration drilling includes recovering core from as close to 100 percent of the drilled interval as possible so there are no gaps in the data and so analyses can be carried out on the entire cored interval, if desired. Fractured rock intervals also cause difficulties during diamond-core-drilling. Problems can include loss of circulation of drilling fluids in porous zones that can lead to premature diamond bit wear, bit failure or potential loss of drilling tools in the hole due to the shifting of fractured rock. The strategy used in siting drill holes in Duluth Complex deposits would not be focused on defining fracture zones; it would attempt to avoid these areas altogether.

This is not to say that mineral exploration drilling cannot provide useful hydrologic or fracture data. However, it is incorrect to conclude that because a certain set of mineral exploration drill holes did not encounter interconnected hydrologic conditions, that interconnected hydrologic conditions do not exist at Minnamax or NorthMet. There have been thousands of mineral exploration and scientific bore holes drilled into the basal Duluth Complex and footwall rocks over the past nearly 40 years. These larger datasets would undoubtedly contain information that would add to the understanding of the interconnectedness of fractures or the presence of pressurized ground water. These data are not presented in the SDEIS.

The quote above from page 4-45 of the SDEIS stating that the upper fractured zone of bedrock has been removed by glacial scouring should be properly referenced or otherwise supported by data to be taken seriously. This statement is not supported by any of the cited references and is contrary to common knowledge that fractured bedrock is present at NorthMet. Drilling logs included in the SDEIS' supplementary materials (PolyMet, 2013i; RS-35, RS-42 and RS-46) show intervals of weathered bedrock at multiple locations thereby reducing the credibility of this statement.

Mine dewatering will lead to an increase in the amount of oxygen that is available to weather rock in pit high walls. This increased weathering rate may be particularly effective at increasing the aperture of bedrock fractures. Rouleau *et al* (2003) reported that mine dewatering causes oxidation of newly unsaturated rock (including fracture surfaces) increasing the rate of chemical reactions thereby affecting groundwater.

The SDEIS incorrectly characterizes the information that is available about bedrock fractures at the NorthMet site and fails to address in any rigorous fashion the potential for long-distance transport of groundwater and contaminants through bedrock fractures.

2.2 Bedrock Hydrogeology – Mine Site

The quotes and comments below are from those sections in the SDEIS that take assumptions made elsewhere about geology and apply them to the hydrology of the NorthMet Mine Site. Here many of the same flawed arguments presented earlier in an attempt to downplay the significance of bedrock fractures reappear as hydrogeologic assumptions that later used to determine model inputs.

> *"Due to the generally low hydraulic conductivity of bedrock, independent calculations indicate that groundwater transport in bedrock is minimal and does not affect solute concentrations at the evaluation locations."* (SDEIS, p. 5-33)

The blanket statement about low conductivity bedrock at the Mine Site is not supported. As mentioned above, the SDEIS has ignored fracture flow in its treatment of groundwater flow at both the Mine Site and the Tailings Basin Site. The conclusion that groundwater transport through bedrock has no effect on solute concentrations can only be reached by ignoring groundwater flow through bedrock fractures, a position that is not scientifically defensible. Assumptions made in the SDEIS about hydraulic conductivity of bedrock at the Mine Site should be revised and better related to actual field conditions.

> *"Bedrock flowpaths and evaluation locations were also evaluated, but because the bedrock (primarily the Duluth Complex) is highly competent with very low hydraulic conductivities (see Table 5.2.2-7), very little groundwater transport occurs within the bedrock flowpaths and travel times to evaluation locations are predicted to be in the thousands of years."* (SDEIS, p. 5-33)

Table 5.2.2-7 shows extremely low horizontal and vertical hydraulic conductivity values of 0.00049 and 0.000049 ft/day respectively for the Duluth Complex. These extremely low values reflect only the rock's primary hydraulic conductivity and therefore do not take into consideration water transmitted through faults, other fractures and secondary porosity features that are known to exist at NorthMet (PolyMet, 2013i). It is true that if rock had such extremely low hydraulic conductivity values, low travel times would result. But applying such low hydraulic conductivity values to the bedrock at the Mine Site as a whole does not accurately reflect field conditions described in other places in the SDEIS as well as in the scientific literature. Considering groundwater flow through fractured bedrock would result in travel times possibly orders of magnitude lower than assumed in the SDEIS. Again, this is major inadequacy of the SDEIS' treatment of hydrogeology.

The SDEIS analysis of water quality impacts (SDEIS, p. 5-33) restates the scientifically unfounded claims made earlier in the SDEIS on page 4-45 that fracturing in Duluth Complex rocks can be dismissed based on their age and the claim that fractures in the Duluth Complex are unlikely to transmit water. (See discussion at pages 4 to 5 above).

As in the prior section, the SDEIS analysis of water quality impacts seems to rely heavily upon old references from studies conducted at locations other than NorthMet while at the same time ignoring more recent high-quality geologic studies from the NorthMet project area itself carried out by the Minnesota Geological Survey (Jirsa *et al*, 2011; Severson and Miller, 1999; Miller and Severson, 2005a; 2005b; 2005c; and 2005d for example) and by PolyMet and its consultants (PolyMet, 2007b and PolyMet, 2013i for example). Chapter 5 of the SDEIS discounts the presence of fractures.

> *"Although the presence of fractures at the Mine Site cannot be completely ruled out, site specific data, such as boring logs, indicate the bedrock appears competent, only rarely encountered deep fractures near the surface, and hydrogeologic investigations have indicated that the bulk hydraulic conductivity of bedrock at the Mine Site is very low."* (SDEIS, p. 5-33)

These statements are not true. As mentioned previously, there is no debate whether fractures exist at the Mine Site; only their detailed hydrologic significance remains unclear. Reports and drilling records presented previously confirm the presence of fractures. The claim that bulk hydraulic conductivity of the bedrock at the Mine Site (or the Tailings Basin for that matter) is low ignores groundwater flow through known and documented fractures. The statement about rarely encountering deep fractures near the surface is irrelevant. Deep fractures occur deep, not near the surface.

2.3 Bedrock Fracturing – Tailings Basin Site

The simplistic approach the SDEIS takes in its treatment of the role of bedrock fractures in groundwater flow is underscored by Figure 3.2-28 of the SDEIS. This figure shows a conceptual cross section of the Tailings Basin, the geologic materials beneath it and the groundwater containment system proposed to be constructed around a part of its perimeter. Figure 3.2-28 portrays the bedrock beneath the Tailings Basin as an "assumed no-flow boundary" in the modeling of groundwater flow through the Tailings Basin and underlying surficial sediments.

The implication of this figure is that groundwater flow through bedrock at the Tailings Basin is so insignificant that it can be conceptually ignored. By accepting the *"no-flow boundary"* assumption, the successful collection of 90 percent or more of contaminated groundwater may reasonable. However this rather critical assumption about very low hydraulic conductivity is not supported by any data or references within the SDEIS. In fact a later section of the SDEIS clearly explains that assumptions must be made in this area because *"hydraulic testing in the bedrock has not been performed in the Tailings Basin area"* (SDEIS, p. 4-95).

Geologic mapping recently published by the Minnesota Geological Survey shows faults to exist immediately beneath the existing Tailings Basin and proposed Hydrometallurgical Residue Facility ("HRF") (Figure 1). A short discussion about geologic map scale and the usefulness of maps such as these is necessary in order to properly address the hydrologic significance of these mapped faults.

The data source for the faults shown in yellow on Figure 1 is a 2011 state-wide digital compilation of geology at a scale of 1:500,000 (Jirsa *et al*, 2011). This type of compilation map involves assembling the largest-scale and most current geologic maps that exist for any individual area and then filtering the geology shown on the individual maps through up-to-date geologic models and summarizing the geology with a unified map legend. Areas not covered by acceptable larger scale maps are then presented with the most accurate and up-to-date interpretation of the geology by those most experienced – staff geologists at Minnesota Geological Survey.

Maps of such small scale as Jirsa *et al* (2011) should be used with caution on site-specific studies, but they shouldn't be entirely ignored either. Most of the areas shown on Figure 1 with yellow faults were mapped at a scale of 1:24,000 in the 1970's and again at 1:100,000 in 2003 and 2005 (Jirsa and Boerboom, 2003; Jirsa *et al*, 2005). Professional practice would suggest that components of these earlier larger-scale geologic maps that are still relevant were incorporated into the 2011 compilation. Figure 1 yellow lines show faults mapped in the 2011 statewide compilation, which is the most current geologic map available for the Tailings Basin area and was prepared by some of the states most qualified geologic mappers.

While the SDEIS fails to acknowledge the fault that exists beneath the Tailings Basin and the proposed HRF, its location is described in PolyMet (2012a), however they suggest there is ambiguity whether this fault exists.

> *"The location of linear valleys is sometimes interpreted to correspond with the location of faults in the bedrock. For example, the Minnesota Geological Survey (MGS) has inferred but not confirmed the presence of a north-south trending fault to underlie the proposed HRF (Reference (6)), Large Figure 4). A bedrock geological map compiled in 2003 by M.A. Jirsa and T.J. Boerboom of the MGS depicts the same area without an inferred fault (Reference (7))."* (PolyMet, 2012a)

The above quote from PolyMet fails to acknowledge Reference 7 (Jirsa and Boerboom, 2003) - that does not show the fault - is an older geologic map than Reference 6 (Jirsa *et al*, 2005) which does show the fault. The fault beneath the Tailings Basin and HRF is shown on all Minnesota Geological Survey bedrock geology maps covering the Tailings Basin site from 2005 to the present (Jirsa *et al*, 2005; Jirsa *et al*, 2011; Jirsa, *et al*, 2012). The reason it is shown on post-2003 geologic maps reflects advancement in the understanding of the geology of the area. New data become available, old data are reevaluated within new geologic models, new outcrops are discovered and simply more hours are spent mapping geology. The above quote from PolyMet also interjects ambiguity by stating the fault has been *"inferred but not confirmed".* Essentially all aspects of geologic maps are inferred because they usually cannot be viewed or measured directly. This fault's location is mapped based on sound geologic inference or it wouldn't be shown. It can't be "confirmed" unless careful excavation was carried out along the entire length of the fault.

The faults shown on Figure 1 in black are from a series of geologic maps published by the Minnesota Geological Survey during the period 1999 to 2005 (Severson and Miller, 1999; Miller and Severson, 2005a; 2005b; 2005c; and 2005d). The scale of this mapping - 1:24,000 - represents some of the most detailed mapping that is publicly available and consequently portrays the geology in more detail and with a somewhat higher degree of confidence than the geology presented in the state-side compilation.

Faults are indeed mapped beneath and in close proximity to the Tailings Basin and HRF (Figure 1) (Jirsa *et al*, 2011) but they may or may not be significant pathways for groundwater and contaminant flow (Golder Associates, 2010). Additional fractures would most certainly be identified in the vicinity of the Tailings Basin if an effort were made to map them. The extent of bedrock fractures and the hydrogeologic properties of fractures at the Tailings Basin and Mine Site are substantially unknown at this time because neither the project proponents nor the Co-Lead Agencies required that they be studied at all. The faults shown on Figure 1 should have been acknowledged early in the environmental review process, and their presence should have triggered additional field studies designed to map the underlying bedrock fracture system and to characterize its hydrologic properties.

2.4 Bedrock Hydrogeology - Tailings Basin Site

In the SDEIS, the entire discussion of bedrock geology and hydraulic conductivity at the Tailings is presented in the following single paragraph.

> *"Hydraulic testing in the bedrock has not been performed in the Tailings Basin area, but the bedrock is believed to have a significantly lower hydraulic conductivity than the overlying drift (Barr 2009f). This is supported by analogy to the bedrock of the Mine Site (Duluth Complex), which, based on hydraulic testing, has been shown to have a significantly lower hydraulic conductivity than the overlying till. The Giants Ridge Granite is mechanically similar the Duluth Complex, which is a gabbro. Assuming relatively similar stress, weathering, and erosional histories, it is likely to have similar hydrogeologic characteristics."* (SDEIS, p. 4-95)

This quote clearly admits that hydraulic testing has not been performed on the bedrock that underlies the Tailings Basin area, yet the seepage containment plan for the Tailings Basin implies that the hydrologic properties of the bedrock here are well enough known to declare the bedrock beneath the Tailings Basin to be a *"no-flow boundary"* (see Figure 3.2-28). Also elsewhere in the SDEIS (p. 4-45 and p. 5-33) the argument is made that the rocks of the Duluth Complex cannot contain faults and fracture zones that could permit transmission of groundwater through the bedrock over long distances. In the paragraph above, due to an admitted complete lack of field data, it is clear that assumptions rather than data have been used to characterize the hydrogeologic properties of the bedrock beneath the Tailings Basin. These assumptions are not reasonable.

Comparison of the Giants Range Granite to the Duluth Complex cannot support assumptions made about hydraulic conductivity at the Tailings Basin. The Giants Range Granite was emplaced about 2,700 million years ago and the Duluth Complex about 1,100 million years ago, that is a difference of 1,600 million years. The Giants Range Granite would have experienced a different stress, weathering and erosional history than the Duluth Complex.

A larger, more serious issue here is the reasoning used in many places within the SDEIS that the age of the rocks, rather than pertinent field data, is somehow the critical attribute controlling fracturing. A thorough understanding of the nature and geometry of the bedrock fractures that are mapped beneath the Tailings Basin and proposed HRF is crucial to predicting how groundwater and contaminants that leach from the Tailings Basin and HRF will migrate. The SDEIS relies on anecdotal assumptions rather than data:

> *"Although these rocks may be fractured to some extent, they are expected to have significantly lower hydraulic conductivity than the bedrock units at the Mine Site."* (SDEIS, p. 4-165)

Any conclusion that the rocks at the Tailing Basin site have lower hydraulic conductivity than the Duluth Complex rocks needs documentation to be considered scientifically valid. Elsewhere in the SDEIS (p. 4-45 and p. 5-33) the argument is made that rock units older than 1.6 billion years are more fractured than younger rocks. If this assumption were true (which it is not), the older rocks of the Giants Range Granite present beneath the Tailings Basin site would be more fractured than the rocks of the Duluth Complex because they are older than 1.6 billion years. In fact, assumptions about fractures based on the age of rock are spurious. What the SDEIS requires is data.

Furthermore, the SDEIS presents conflicting data in Table 5.2.2-7 where hydraulic conductivity values used as MODFLOW inputs for the Giants Range Granite are shown as being several orders of magnitude <u>higher</u> than the rocks of the Duluth Complex, not significantly lower (from Table 5.2.2-7: mean hydraulic conductivities: GRG = 0.026 ft/day vs. DC = 0.00049 ft/day). These blatant contradictions in the reasoning used to portray the hydrogeology of the NorthMet site need to be resolved before the SDEIS can be considered scientifically adequate.

Overgeneralization of the hydrogeology setting at the Tailings Basin site has led to a simplistic model of contaminant transport from the Tailings Basin that does not accurately reflect documented field conditions.

> *"At the Plant Site, most groundwater flow occurs in an unconfined surficial groundwater system composed of unconsolidated sands, silts, and clays, and has a saturated thickness on the order of 7 meters. Below the surficial groundwater system is a low-permeability fractured bedrock unit consisting of several rock types. Groundwater flow rates in the bedrock unit are much less than flow in the overlying surficial groundwater system."* (SDEIS, p. 5-68)

Since no field studies were carried out to characterize the glacial sediments at the Tailings Basin site (Barr, 2009f) or to measure the hydraulic properties of the bedrock they overlie (SDEIS p. 4-95), only anecdotal comparisons can be made regarding the hydraulic conductivity of the various geologic materials. The above statement reiterates what is stated elsewhere in the SDEIS; that the bedrock at the NorthMet site does contain fractures, but then concludes that groundwater flow through these fractures is insignificant. As discussed previously, arguments presented in the SDEIS to downplay the hydrologic significance of bedrock fractures are scientifically invalid.

It is true that the permeability and primary hydraulic conductivity of the Giants Range Granite beneath the Tailings Basin would be low when compared to the overlying unconsolidated sediments. But the permeability and hydraulic conductivity of the entire bedrock system beneath the Tailings Basin – one that that includes fractures - would likely be several orders of magnitude higher than presented in the SDEIS. Unless a solid scientific basis is provided, the SDEIS' claims - both explicit and implicit - that groundwater flow through fractured bedrock is minimal, cannot be sustained. Field studies including characterization of the hydrologic properties of bedrock fractures would provide valuable data to determine whether bedrock fractures present at the NorthMet site are hydrologically significant and the potential direction of seepage flows. The scientific literature and general professional knowledge of the region's geology suggests that bedrock fractures will play a significant role in groundwater and contaminant transport at both the Tailings Basin and the Mine Site.

The SDEIS statement that groundwater flow through bedrock is *"negligible"* provides no quantitative assessment, but appears to assume that the bedrock beneath the Tailings Basin is essentially incapable of transmitting groundwater and contaminants. The concept that most of the subsurface drainage from the Tailings Basin can be effectively captured is based on this flawed anecdotal reasoning, not on sound science.

The implications of an overly simplistic view of the surficial and bedrock geology presented for the Tailings Basin site result in a model that presents a very simple flow concept, which is then used to confidently predict very effective capture and contaminant using engineered solutions.

> *"As at the Mine Site, once most of the contaminants are released, they are assumed to travel in the same direction and rate as groundwater (accounting for some dispersion) and ultimately reach surface water. Groundwater flow rates and flow directions in the model were taken directly from the MODFLOW results or were programmed to be consistent with the MODFLOW results. Unlike the Mine Site, however, PolyMet proposes a containment system along the northern and western perimeters of the Tailings Basin to intercept surficial groundwater and surface water seeping from the Tailings Basin. Design and performance modeling of the containment system predict that it would achieve greater than 90 percent capture of upstream groundwater in the surficial (unconsolidated) unit (PolyMet 2013f). In GoldSim, the containment system is conservatively assumed to be 90 percent efficient, which means that 10 percent of the approaching groundwater bypasses the system and continues to migrate toward the Embarrass River via the surficial groundwater flowpaths. This affected groundwater migrates in the flowpaths to the north, northwest, and west, and concentrations change progressively at the evaluation locations. The affected groundwater reaches and releases directly into the Embarrass River (West Flowpath) or into its tributaries (Northwest and North flowpaths). Due to the very low hydraulic conductivity of the bedrock and because the slurry trench would be keyed into bedrock, the GoldSim model assumes that groundwater bypass via bedrock is negligible compared to that occurring in the surficial unit."* (SDEIS, p. 5-68-69)

First, the statement about construction of a slurry wall that is keyed into bedrock is in direct conflict with SDEIS Figure 3.2-28 that shows no keyed relationship between the proposed slurry wall and the bedrock beneath the Tailings Basin site. This is a very important aspect that has direct bearing on the effectiveness of the engineered system designed to capture contaminated groundwater emanating from the Tailings Basin.

Slurry walls are constructed by excavating continuous trenches around the perimeter of an area that is desired to be hydrologically isolated. Techniques used to construct slurry walls involve excavating downward from the surface, commonly using a clam-shell type bucket. In order to keep the walls of the trench from collapsing during excavation, whether excavation is taking place above the water table or below, high-density fluids such as drilling mud are used to keep the walls of the trench from collapsing. Upon completion of the excavation to the desired depth this high-density, oftentimes bentonite mud is thickened and left in the trench providing the “impermeable” slurry wall. One of the most important aspects of constructing a slurry wall that effectively blocks the flow of groundwater is the nature of the geologic materials into which the slurry wall will terminate.

In the Denver area, slurry walls are commonly constructed during the process of mining gravel. Upon cessation of mining the depleted gravel pits are reclaimed for use as surface water reservoirs. The success of slurry walls constructed in this geologic setting relies on the presence of favorable geologic materials into which the slurry wall can be “keyed”. The successful application of slurry wall technology used in the Denver area results from the presence of Cretaceous black shale called the Pierre Shale at the base of the sand and gravel deposit. Pierre Shale is quite impermeable yet rather easily excavated using a clam-shell type bucket from the surface.

The geologic situation at the Tailings Basin is not favorable for the typical slurry wall construction technique of keying the slurry wall into bedrock because the bedrock present at the Tailings Basin is granite. This type of rock cannot be easily excavated from the surface using typical slurry wall construction techniques. It is difficult to imagine how construction of an effective slurry wall could be accomplished in this geologic setting without completely dewatering the perimeter of the Tailings Basin, followed by the blasting of a trench into the Giants Range Granite that would serve as the “key” into which the slurry wall the slurry wall would be sealed.

Further complicating construction of any type of seepage containment system at the Tailings Basin would be the presence of a very boulder-rich glacial till (Figure 3). In fact the boulder-rich characteristics of this particular Rainy lobe till are so obvious that researchers from the U.S. Geological Survey named it “the bouldery till” (Winter, 1971; Winter *et al*, 1973). The high percentage of boulders present in this till caused numerous problems in penetrating certain zones during field tests carried out at the Tailings Basin (Pint and Dehler, 2008; PolyMet, 2013n) and at the Mine Site (Barr, 2006b). One additional challenge posed by the presence of boulder-rich till in the construction of a slurry wall around certain portions of the Tailings Basin would be the inability to determine whether slurry wall excavation has actually encountered bedrock or possibly just a very large boulder in the till (Figure 3). Barr’s (2007g) report to PolyMet on the construction of seepage capture systems at the Tailings Basin recognizes that slurry walls are not suitable if boulders or cobbles are present. The details of how an effective slurry wall system could be constructed at the Tailings Basin - one that takes into account actual field geologic conditions - seems to be missing from the SDEIS and supporting documents. Barr Engineering has reportedly designed a seepage collection system for the Tailings Basin with sufficient detail for Ames Construction to have prepared a bid to construct the seepage collection system (Desautels and Zurowski, 2012). These construction plans contain important details that are necessary to understand the assumed effectiveness of the seepage collection system and to predict impacts on groundwater quality should the slurry wall not function as predicted. These critical plans should be made available for review as part of the environmental review process.

The subject of contaminant transport from the Tailings Basin seems not to take into account surface drainage conditions and the resulting near-surface groundwater flow conditions that existed prior to the construction of the LTVSMC tailings basin. The quote above from pages 5-68 to 69 in the

SDEIS fails to consider groundwater flow emanating from the south side of the Tailings Basin (SDEIS, p. 5-89) and is not supported by PolyMet's consultant reports.

> *"At the southern end of the Tailings Basin there is some ground water flow to the south from Cell 1E forming the headwaters of Second Creek. As the Tailings Basin was built up over time, a groundwater mound formed beneath the basin due to seepage from the basin altering local flow directions and rates. Active seeps have been identified on the south, west and north sides of the Tailings Basin….groundwater likely flows out from beneath the tailings basin into the surrounding glacial deposits to the south, west and north of the basin."* (Barr, 2009f, P. 3)

Examination of U.S. Geological Survey topographic maps from 1949 that predate tailings basin construction show that about one-third of the area currently beneath the southern portion the Tailings Basin or about 1,000 acres, historically drained to the south and formed the headwaters of Second Creek (Figure 4, Figure 5). The remainder of the area currently beneath the Tailings Basin, or about 1,900 acres, historically drained to the northwest and north. The recognition that 1,000 acres of the sub-tailings basin watershed originally drained to the south into Second Creek is in disagreement with the SDEIS' characterization of this being a "small area" (SDEIS, p. 5-89).

Groundwater seeps that flow naturally into the headwaters of Second Creek are known to exist on the south side of the Tailings Basin (SDEIS, p. 5-89; PolyMet, 2012a) where the design of any new proposed engineered seepage capture system seems to ignore groundwater flow south out of the Tailings Basin and into alluvial sediments that make up the now highly altered upper reaches of Second Creek. An existing capture and pump back system is apparently in place at this location (SDEIS, p. 5-89). Its ongoing performance should be addressed in this section of the SDEIS as well as how proposed changes to the Tailings Basin hydrology over the 20-year mine life will affect these seeps and the existing seepage collection system.

The SDEIS also does not acknowledge existing seepage along the east side of the Tailings Basin (Seep 31 shown on Figure 6 in Barr, 2007g) nor discuss how the historic streams flowing from Spring Mine Lake may affect groundwater flow to the east from beneath the Tailings Basin. The placement of NorthMet tailings into Cells 1E and 2E is proposed to raise the elevation of these cells to the same elevation as the western cell of the tailings basin by the time of closure or to an elevation of 1,735 feet above sea level (SDEIS, p. 3-102). This higher land surface will result in an elevated water table within the eastern cells of the tailings basin just as the western cell has. The water table will remain high for possibly hundreds of years or longer due to pump back of seepage captured from the perimeter of the Tailings Basin. It is conceptually possible that this increase in head within the Tailings Basin will eventually result a reversal of groundwater flow within the alluvial sediments present in the valley of the stream flowing west from Spring Mine Lake. According to high resolution LiDAR topographic data the current elevation of the water plane within Cell 1E is about 1,650 feet in elevation and the elevation of Spring Mine Lake is 1676 feet in elevation, thereby preserving the natural relationship where Spring Mine Lake is higher than the tailings basin area, so that groundwater in valley of the creek flowing westward from Spring Mine Lake still likely flows toward the Tailings Basin. However, at closure Cell 1E will rise 59 feet above the surface of Spring Mine Lake reversing this topographic relationship. The potential for seepage from the Tailings Basin towards the east due to these current and forecast conditions and the potential need for a seepage collection system on the east side of the Tailings Basin seems to have been overlooked in the SDEIS.

Of particular interest to the subject of contaminant transport from the Tailings Basin is the amount of nickel that is unrecoverable during processing and will end up in the Tailings Basin. Most of the nickel in the NorthMet deposit occurs in sulfide minerals, most notably pentlandite (PolyMet, 2007b). Most of the nickel occurring in sulfide minerals will be recovered during processing, but according to PolyMet's own report (2007b) there is a *"25 to 35% loss of nickel to silicates."* In other words, of the total amount of nickel that exists in the NorthMet deposit a maximum of only 65 to 75% is expected to be recovered and 25 to 35% will end up in the Tailings Basin bound up in silicate minerals. Nickel occurs in silicate minerals where nickel ions replace iron and magnesium ions within the crystal lattice of minerals such as olivine. This nickel cannot be economically recovered from the olivine so the nickel-bearing olivine mineral grains end up deposited in the Tailings Basin.

What is particularly notable about the situation of nickel in the tailings is that elsewhere the SDEIS presents evidence to suggest that low sulfur rock (< 0.12% S) has little risk for acid generation due to the buffering capacity of calcium that is released from silicate minerals such as pyroxene (diopside) and calcic plagioclase feldspar.

> *"there are essentially no acid-neutralizing carbonate minerals in NorthMet waste rock, but silicate minerals—including plagioclase feldspar ([Na,Ca][Si,Al]4O8), olivine ([Mg,Fe]2SiO4), and pyroxenes (e.g., diopside, MgCaSi2O6)—neutralize some acid, which would delay acid onset in some rock and would prevent entirely the onset of acidic conditions in rock with less than 0.12 percent sulfur"* (SDEIS, p. 5-51)

Weathering results in the release of calcium ions from the lattice of these minerals. The same weathering process that liberates calcium to buffer acid will also cause nickel to be released from the lattice of olivine.

The presence of large amounts of nickel in silicate mineral tailings exacerbates potential water quality issues due to surface area of olivine tailings, which will be sized as fine sand or silt. It is well-known that mobilization of elevated concentrations of nickel does not require acid conditions (SRK, 2007b), and that under commonly-occurring conditions, olivine generally weathers before pyroxene and plagioclase (Goldich, 1938). Waters flowing through the tailings piles will be oxygen-rich due to the continual pump-back of captured seepage, further contributing to accelerated release of nickel from olivine. This situation where large amounts of nickel are weathering from silicate minerals within the Tailings Basin coupled with the likelihood that significant volumes of seepage will escape capture from around the Tailings Basin is likely to lead to excessive levels of nickel migrating off-site. The SDEIS should explicitly analyze the *"loss of nickel to silicate"* issue, in light of the hydrogeology of the Tailings Basin.

3.0 SURFICIAL GEOLOGY

At both the Mine Site and the Tailings Basin, a variety of distinct Precambrian bedrock units are overlain by a discontinuous variable thickness of sediments deposited in association with the advance and retreat of multiple continental glaciers. In many places at both the Mine Site and

Tailings Basin these glacial sediments are in turn overlain by post-glacial peat accumulations. The bedrock surface topography is highly irregular with outcrops common in many areas at both sites.

A scientifically sound understanding of the three dimensional distribution of the variety of surficial sediments present at the Mine Site and Tailings Basin and an accurate characterization of their range of physiochemical properties must be achieved for a number of important reasons including the following: 1) Surficial sediments represent the overburden that must be stripped and stockpiled, and possibly used in construction, in a way that minimizes risks to water quality and human health. The physiochemical properties of these materials must be well understood in order to effectively manage these risks; 2) Surficial sediments will form the foundations of the various stockpiles proposed to be built and make up the foundation of the current LTVSMC tailings basin. They provide either barriers or pathways for groundwater leaching through stockpiles and tailings impoundments; and 3) Surficial sediments are the container for near-surface groundwater and they provide the medium for the interaction of process water, surface water in wetlands and streams and groundwater in surficial materials and in bedrock.

Generalizations based on assumptions are made throughout the SDEIS to infer the physiochemical properties and distribution of surficial sediments. These assumptions are then used to infer hydrologic conditions that are in turn used as inputs and in calibration of predictive models. In general the approach taken towards understanding the surficial geology of the Mine Site and Tailings Basin in the SDEIS is very simplistic.

3.1 Surficial Geology – Mine Site

The discussion of the surficial geology of the Mine Site begins with the following statement.

> *"The surface material that would be encountered by the NorthMet Project Proposed Action mining include a relatively thin (0 to ~59 ft thick) surficial layer of unconsolidated glacial till."* (SDEIS, p. 4-43)

This is one of several instances within the SDEIS where the entire assemblage of surficial sediments is described using a term more correctly reserved for specific types of surficial sediments. The word *"till"* here is used in sort of a slang fashion to refer to all of the surficial materials that occur at the Mine Site, including well-sorted sediments which, by definition are not *"till."* In addition, 60 feet of surficial sediment is not "thin;" there can be a variety of different types of sediments with different hydrologic properties present within a surficial section this thick.

Another example of overgeneralization of Mine Site surficial geology:

> *"Water table elevations measured by PolyMet in Mine Site bedrock boreholes indicate that the hydraulic gradient is similar to that of the overlying alluvium (sloping down to the south and southeast across the Mine Site), consistent with a hydraulic connection between the alluvium and bedrock units (PolyMet 2013i)."* (SDEIS, p. 4-46)

A few pages above, the term "till" was used as a general term, now in this paragraph the term "alluvium" seems to be used as a replacement term for all surficial sediments. On page 4-149 the entire package of surficial sediments is referred to as "soil". This is more than semantics; it leads to confusion as to exactly which surficial sediments are being referenced: the entire surficial sediment section or only till units or only alluvium units or only the post-glacial soil that exists at the land surface? This usage promotes a simplistic understanding of surficial geology, which in turn is converted into overly simple and inaccurate inputs to predictive models.

In addition to till, other surficial sediments present at the Mine Site include lacustrine sediments and outwash sand and gravel (PolyMet, 2007b; Barr, 2006b). The rotasonic drilling program reported *"a highly compacted gray clay unit with numerous pebbles was encountered just above bedrock in several borings"* (Barr, 2006b). This unit likely represents one or more individual older till units that are known to exist in the area of the eastern Mesabi Range (Winter, 1971; Winter *et al*, 1973; Lehr and Hobbs, 1992). These various surficial sediments have widely ranging textures and different weathering histories and therefore potentially widely ranging hydrologic properties.

Rather than describe Mine Site geology, the SDEIS provides regional generalizations.

> *"This surficial till is relatively young (~14,000 to 60,000 years old), and has been described at a regional scale as unsorted sandy loam mixture with pebbles, cobbles, and boulders (Jennings and Reynolds 2005)."* (SDEIS, p. 4-43)

This statement doesn't accurately describe Mine Site surficial sediments. First, there is more than one till unit at the Mine Site (PolyMet, 2013i; Barr, 2006b). Drilling logs in these reports provide numerous examples where multiple tills were encountered during drilling at the Mine Site. In some instances multiple tills are separated by intervals of outwash sand and gravel - some that are greater than 10 feet thick (RS-11 for example in PolyMet, 2013i). The thickness and extent of these outwash zones in the subsurface should have received more attention in the SDEIS; they represent significant pathways for groundwater flow and contaminant transport.

The surficial Rainy lobe till maybe about 14,000 years old, but not anywhere near 60,000 years old. Older tills that occur stratigraphically below the surficial Rainy lobe till may be 60,000 years old but could be much older (Lehr, 2000). The patchy older tills that are known to exist along the eastern Mesabi Range (Winter, 1971; Winter *et al*, 1973; Lehr and Hobbs, 1992) could have been deposited during several different glacial episodes over the past couple of million years, with the patchwork of older tills surviving erosion for that long having been somewhat protected from glacial erosion by the topographic lee created by the crest of the Giants Range (Lehr and Hobbs, 1992; Lehr, 2000).

This age distinction isn't trivial because a till with a 14,000 year weathering history will have been subject to a much shorter period of weathering than a till perhaps millions of years old. The different weathering histories of the various tills result in different physiochemical properties. Further hydrologic significance related to older tills, especially those that are more clay-rich, is that they oftentimes exhibit strong vertical jointing especially compared to tills deposited during the last glacial episode. Tills that have undergone glacial isostatic flexing are fractured just like bedrock. The joints present in older relatively fine-grained till are fractures that have the potential to transmit groundwater just as bedrock fractures do (Golder Associates, 2010), another situation that seems to have been overlooked in the SDEIS.

The simplistic conceptual model of surficial geology at the Mine Site has resulted in a very simple and likely flawed plan to mitigate water quality problems that may arise from the presence of sulfur and metals in the overburden.

> *"Three types of overburden are present at the site: unsaturated overburden, saturated overburden, and peat. Each type of overburden would be managed according to its potential to be reactive (i.e., acid-producing through oxidization of iron sulfides)."* (SDEIS, p. 3-44)

Surficial materials at the Mine Site are heterogeneous, so a simplified approach to predict and mitigate acid generation and metal leaching from overburden stockpiles and construction with overburden materials may be ineffective. Overburden at the Mine Site contains a diverse assemblage of glacial sediments that includes multiple tills, lacustrine sediments, and outwash sand and gravel (PolyMet, 2007b) that is overlain in many places by post-glacial peat accumulations. An effective plan to mitigate impacts of contaminated water discharging from overburden stockpiles at the Mine Site requires consideration of the physical properties of these materials.

Unsaturated and saturated are not *"types of overburden"*, but rather these are terms that describe a hydrologic condition of the sediments that comprise the overburden at a particular time. The obvious should be pointed out here and that is that none of the overburden at the Mine Site – glacial sediments or peat - will be saturated by the time it is removed and placed in stockpiles. The water levels in the overburden will have been lowered by pumping (dewatered) to allow for the removal of previously saturated overburden with large-scale excavating equipment. As soon as the overburden material begins to drain during dewatering, the oxidation rate of sulfide minerals will increase and mobility of metals will increase along with the resulting decrease in pH.

Whether overburden is saturated or unstaturated may not have a direct bearing on its potential to generate acid or leach metals. For example, unsaturated sand and gravel would likely contain fewer unweathered sulfide mineral grains and more sulfide-mineral weathering by-products due to availability of greater amounts of oxygen in that porous sediment than might unsaturated clayey lacustrine sediments or many varieties of till. The assumption that the boundary between acid-generating overburden and non-acid generating overburden at NorthMet coincides precisely with the water table directly contradicts an entire body of geologic literature known as "drift prospecting" or "drift exploration" and is therefore most likely flawed. The vast drift prospecting literature has received extensive peer review, and the SDEIS has not.

Drift prospecting techniques have long been used with great success across the Precambrian shield areas of North America and Fennoscandia to target ore deposits in the bedrock (see papers included in DiLabio and Coker, 1989, and McClenaghan *et al*, 2001 for example). In addition to the papers presented in the two previously cited references that represent international research on the subject of drift prospecting, the Minnesota DNR Division of Lands and Minerals has an extensive catalog of "drift prospecting" studies that they have carried out over the years to promote mineral exploration.

A commonly used technique in drift prospecting studies involves collecting a set of samples from glacial till and analyzing them for ore minerals, ore tracer minerals and chemical signatures that are indicative of ore deposits. The ore minerals and ore tracer minerals often occur in the sand size fraction of the till while the chemical signatures that result from weathering of ore minerals are usually found in the silt and clay fraction (minus 63 micron fraction). When the results of this type of survey are mapped and scrutinized using a sound understanding of glacial and bedrock geology, trends sometimes become apparent and the location of ore deposits are revealed by what are called **dispersal trains**. One salient characteristic of mineral or chemical dispersal trains is that they often display a very predictable decrease in the concentration of ore deposit indicators in the down-ice direction from the ore deposit. In other words the concentration of ore deposit indicators within till in the vicinity of mineral deposits is most often greatest on top of the ore deposit and immediately down-ice and then decreases systematically in the direction of glacier flow.

Since many common metallic ore minerals are sulfide minerals, they are susceptible to weathering in the oxidized upper portion of the glacial sediments that overlie bedrock. Till sampling techniques employed in drift prospecting studies commonly involve hand-digging holes in areas where till occurs at the surface, but only to a depth where the till is at least relatively unoxidized; not to the point of reaching saturated material. This objective is often achieved by digging a hole only about 3 feet deep in many areas on the Canadian Shield.

Sometimes elevated levels of metals occur within the modern soil at the land surface near ore deposits. Anomalous concentrations of Cu, Ni, Co, Ag, Pt, Pd and Au are documented to occur in the fine fraction of B-horizon soils in association with basal Duluth Complex ore deposits in the vicinity of NorthMet (Alminas, 1975; Alminas and Dahlberg, 1994). This suite of ore metals often occurs in association with elevated levels of As, Sb, Zn, Pb and Hg also liberated from sulfide minerals by weathering.

If the assumptions in the SDEIS about the benign acid generating potential and low metal content of unsaturated overburden were true, then the till sampling techniques used in drift prospecting studies would not work unless till samples were collected from saturated material. Based on countless peer-reviewed studies, this is not true. Any NorthMet geochemical test results from unsaturated overburden presented in support of the overburden management plan in the SDEIS would be very sensitive to the texture of the material chosen for testing and its age and yet neither the SDEIS or PolyMet (2013l) report what types or textures of unstaturated overburden were subjected to geochemical analyses. As discussed previously as well as in the literature supporting the SDEIS, the assemblage of surficial sediments (overburden) at the NorthMet site is heterogeneous, ranging from clay and till to sand and gravel. Sediments present within in the Mine Site overburden have widely ranging physical and hydrologic properties that will govern the rate of sulfide mineral weathering and mobilization of metals.

The spatial variability in texture displayed in sediments and sedimentary rocks is referred to as sedimentary ***facies***. The various facies or subunits of surficial Rainy lobe till mapped within the area of the eastern Mesabi Range are texturally quite variable, particularly at former ice margins where melt water played a larger role in deposition (Lehr, 2000; Jennings and Reynolds, 2005). The ice-marginal facies of Rainy lobe till include more numerous layers of permeable sand and gravel and will oxidize more rapidly than more compact subglacial Rainy lobe till. Finally, some of the older sediments that are known to exist within the project area are described as *"very dense clay"* (Barr, 2006b; PolyMet, 2013i). Fine-grained sediments may be very effective at minimizing the oxidation of sulfide minerals even within the unsaturated zone due to their density and high clay content.

The subject of whether unsaturated (but unoxidized) overburden has the potential to create acid or leach metals is an important one. The SDEIS assumes that all unstaturated overburden is benign.

> *"Unsaturated overburden is the material that has been above the natural water table and exposed to air long enough for chemical reactions to have taken place."* (SDEIS, p. 3-44)

This statement is unsupported and misleading. Chemical reactions have taken place in the overburden, especially in the unsaturated portion (vadose zone), but also in the saturated zone, just at a slower rate. What is implied with this statement is that a long enough period of time has elapsed since the deposition of overburden sediments for vadose zone weathering to have to have completely converted sulfide minerals into products that will not generate acid or leach metals. This statement neither takes into account drift prospecting literature which has documented metals in fine fractions of till collected from the vadose zone even when the sulfide minerals themselves have been completely weathered; nor the fluctuation of groundwater levels between the time the oldest overburden sediments were deposited and the present time.

Local field evidence supports the presence of incompletely leached and weathered older tills. I have personally collected Paleozoic carbonate fossils from an oxidized, unsaturated till that occurs immediately below the surficial Rainy lobe till at the Dunka Pit. The presence of pristine carbonate fossil material within the unsaturated oxidized zone of older tills of the eastern end of the Mesabi Range is an indication of very incomplete leaching of certain unsaturated yet oxidized surficial sediments.

Unless and until data or references are provided, SDEIS claims that unsaturated overburden at NorthMet does not contain acid generating or metal leaching materials are unreliable.

> *"The overlying surficial sediments at the Mine Site are poorly sorted and range from very dense clay to well-sorted sand with boulders and cobbles (Barr 2006b; Golder Associates 2007). Hydraulic testing of the surficial sediments indicates that these sediments may contain layers of relatively low hydraulic conductivity (e.g., comparable to the Duluth Complex)."* (SDEIS, p. 4-45)

As discussed previously, detailed knowledge of the three-dimensional spatial relationships amongst the various surficial sediments allows for accurate prediction of the hydrologic properties of the surficial sedimentary package and its relationship to the bedrock hydrologic system. In reports such as the SDEIS where geology plays such an important role, subsurface data such as drilling and trenching results are customarily portrayed using geologic cross-sections and maps that show the spatial relationships that exist amongst the various sedimentary units and their relationship to the bedrock surface. Geologic cross-sections showing the spatial distribution of these *"layers of relatively low hydraulic conductivity"* and the relationship of these sediments to the irregular bedrock surface across the entire NorthMet project area are missing from the SDEIS.

> *"Tests using wells that penetrate through the surficial zone, however, found much higher average hydraulic conductivity, with values similar to the Biwabik Formation aquifer (see Table 4.2.2-5).* (SDEIS, p. 4-45)

The above statement from the SDEIS correctly acknowledges the heterogeneity of hydraulic conductivity values for surficial sediments present at the Mine Site. Unfortunately, this range of variability is not retained in model inputs; instead average hydraulic conductivities seem to be used. The importance of understanding the three-dimensional distribution of surficial sediments to accurately predict ground water flow and chemistry cannot be understated.

Some of the zones encountered during drilling with *"much higher average hydraulic conductivity"* likely represent eskers and related outwash sediments that are known to exist at the Mine Site and at the Tailings Basin Site. Figure 6 shows the distribution of surficial sediments and glacial landforms in the vicinity of the Mine Site prepared by separate mappers (Jennings and Reynolds, 2005; Lehr and Hobbs, 1992; Lehr, unpublished mapping, 2010-2014).

Most of the Mine Site is underlain by three different types of till (Jennings and Reynolds, 2005). Of the three till units mapped at the Mine Site two occur mainly in the eastern portions of the Mine Site in close association with bedrock outcrops (Figure 6). These two eastern till units (*Rainy Lobe Till* and *Water Eroded Rainy Lobe Till*) contain fewer sand and gravel lenses relative to the till unit mapped over the western one third of the Mine Site (Jennings and Reynolds, 2005). The map unit *Re-sedimented Rainy Lobe Till and Sorted Sediment* shown over the western one third of the Mine Site is a hybrid map unit consisting of both re-sedimented till and sorted sand and gravel (Jennings and Reynolds, 2005). The occurrence and distribution of sand and gravel layers reported to be present within this till mapping unit will have significant bearing on the movement of groundwater through the surficial sedimentary package. Perhaps of most significance, this hybrid till and sand and gravel mapping unit with higher hydraulic conductivity appears to underlie much of the area where the unlined Category 1 waste rock stockpile is proposed to be built (Figure 6).

Bedrock outcrops are more common in the eastern two thirds of the mine site (Figure 6) occurring amongst areas of probably rather thin till. Of note is the entire lack of bedrock outcrops mapped within much of the area underlain by the hybrid till/sand and gravel unit. This observation indicates that the overall thickness of glacial sediments is greater and therefore likely more heterogeneous beneath the eastern one third of the Mine Site. In other words, sand and gravel layers will be more commonly interbedded with till in this area thereby creating high hydraulic conductivity pathways for contaminated groundwater.

There are the numerous esker segments visible on the LiDAR topographic imagery for the Mine Site (Figure 6). Eskers can be hydrologically significant because they are linear, ridge-like landforms composed of sand and gravel and for that reason could provide high hydraulic conductivity pathways for contaminated groundwater flow. Note that several eskers are mapped between the boundary of the Mine Site and the Partridge River both north and south of the Mine Site. Also note the esker segments mapped in the vicinity of the Category 1 waste rock stockpile. These eskers were not shown on Jennings and Reynolds (2005) map because detailed topographic data were not available to the Minnesota Geological Survey at that time, but detailed (2-foot contour) topographic mapping of the Mine Site has been available to PolyMet and its consultants since 1999 (PolyMet, 2007b). These eskers may represent conduits for groundwater to flow, yet their presence and significance is not acknowledged within the SDEIS.

Both Jennings and Reynolds (2005) and Lehr (Lehr and Hobbs, 1992; Lehr unpublished mapping 2010-2014) have mapped a Rainy lobe ice margin transecting the southwest corner of the Mine Site. This is significant to the hydrogeology of the Mine Site because the glacial ice-marginal depositional environment contains copious amounts of melt water that mobilizes unsorted glacial debris to produce a heterogeneous assemblage of interlayered till and sorted sand and gravel layers. In many places along the eastern Mesabi Range including portions of the NorthMet project area the Rainy lobe was fronted by a glacial lake (Jennings and Reynolds, 2005; Lehr and Hobbs, 1992). Ice-marginal sedimentation by glacial melt water and gravity into the ice-marginal pro-glacial lake environment resulted in large amounts of sand and gravel deposited directly where the ice margin terminated in the lake. Linear belts of sand and gravel commonly marking the former positions of the Rainy lobe ice margin where it retreated through northeastern Minnesota and northwestern Ontario (Sharpe and Cowan, 1990; Lehr, 2000; Lehr and Hobbs, 1992) are an indication of the widespread conditions that promoted ice-marginal sand and gravel deposition across portions of the NorthMet site.

> *"Shallow borings and test trenches at the Mine Site encountered bedrock at depths ranging from 3.5 to 17 ft below ground surface (bgs). The site exploration drilling database, drilling logs, and electrical resistivity data were used to develop an estimated depth-to-bedrock isopach map (Golder Associates 2007)."* (SDEIS, p. 4-45)

A figure showing this isopach map inserted at this point in the SDEIS would be very helpful in envisioning how the surficial sediment type and thickness varies across the Mine Site. But this map neither appears in the SDEIS or among cited reference documents. The Table of Contents for Golder Associates (2007) lists the isopach map, but the file does not appear in the MDNR DVD set and was not available for review. A detailed bedrock topography map would also be useful at several places in the SDEIS to illustrate where features such as troughs and bedrock valleys are located on the bedrock surface and to assess pathways that may transmit contaminated groundwater at the interface of the overburden and bedrock.

> *"Although the isopach contouring indicates local depressions in the bedrock where estimated surficial cover thickness reaches 50 ft, no major areas of highly permeable outwash sands and gravel have been reported that might serve as groundwater conduits through the unconsolidated material."* (SDEIS, p. 4-46)

Whatever *"major areas"* means, the presence of highly permeable outwash within the overburden is important. Knowing dimensions of sand and gravel outwash layers within the overburden and their orientation would help predict where groundwater conduits and seeps will be located within the overburden. It appears that no surficial geologic maps for the project areas were prepared specifically for the environmental review process. This is a serious deficiency in a geologic data set that underpins so much of the predictive modeling that is presented in the SDEIS. The SDEIS, in addition, ignores most of the detail in published surficial geologic maps for the area. With respect to geology, the result is a data-poor environmental review process.

The supplemental photographs included in Jennings and Reynolds (2005) provide specific examples from eastern Mesabi Range mines where geologic materials occur within the overburden that could act as groundwater conduits and seeps. Figure 7 shows two photos from the Embarrass mine 7 miles west of NorthMet and one photo from the Dunka pit about 7 miles northeast. The two photos from the Embarrass mine show cross-sections through crudely tubular-shaped gravel bodies that are surrounded by finer grained sediments. The photo from Dunka pit shows what looks more like a tabular layer of gravel sandwiched between two separate tills (Figure 7). These are commonly occurring geologic conditions. Similar conditions are likely to exist at the NorthMet site, and would provide high hydraulic conductivity pathways for groundwater and contaminants to flow at rates much higher than the surrounding sediments.

The above statement from page 4-46 of the SDEIS about a lack of outwash sand and gravel at the Mine Site is in disagreement with several drilling logs included in the supplementary materials (PolyMet, 2013i). Each of the drill holes listed in the table below encountered what was described as either outwash or clean sand or gravel or some combination thereof.

Hole	Interval (ft)	Thickness (ft)	Material
OB1	0-8	8	rock & sand
OB2	0-6	6	rock & sand
OB3	0-7	7	rock & sand
P3	5-17	12	sand & gravel
RS-04	24-25	1	gravel
RS-5A	10-13	3	gravel
RS-07	6-11	5	gravel
RS-07R	6-10	4	gravel
RS-11	17-28	11	outwash
RS-12	2-5.5	3.5	outwash
MW-05-08	4-19	15	clean sand
RS-10	5.5-7.5	2	clean sand
RS-39	1-4.5	3.5	clean sand
RS-41	15-21	6	clean sand
RS-45	9.5-19	9.5	clean sand
RS-52	24.5-30	5.5	clean sand

The spatial distribution of permeable outwash layers and their hydrologic significance must be considered for accurate modeling of groundwater flow, but this has not happened in the SDEIS. PolyMet has carried out extensive geologic field investigations at the NorthMet Mine Site and they do report outwash to be present within the overburden (PolyMet, 2007b; 2013i). For example drill hole RS-11 was drilled to a depth of 33 feet using the highly accurate rotasonic drilling method. The drilling log for RS-11 shows an 11-foot-thick interval of sand and gravel outwash sandwiched between two separate till units (PolyMet, 2013i). Two samples were collected from the core recovered from this outwash interval and were submitted for grain size analyses resulting in gravel-sand-fines ratios of 35-59-6 (17 to 25 foot interval) and 23-67-10 (25 to 28 foot interval) (PolyMet, 2013i).

Even where field data was available, it appears that it has been misused in preparing SDEIS models. In a section of PolyMet, 2013i entitled "Updates to Mine Site MODFLOW Model Calibration and

Predictive Simulations" there a discussion of hydraulic conductivity values for surficial sediments used in calibrating the MODFLOW model is presented. It is explained that aquifer testing data from 9 monitoring wells screened in the unconsolidated deposits resulted in estimates of hydraulic conductivity values ranging from 0.12 to 30 ft/day (PolyMet, 2013i). The paragraph goes on to describe how grain-size distribution data resulting from samples collected from 19 rotasonic borings were used to estimate hydraulic conductivity according to a method described as *"Barr, 2001"*. Hydraulic conductivity values were averaged for borings with multiple samples. *"Two grain-size samples were excluded from the average hydraulic conductivity calculation at one location (RS-11) due to anomalously high values associated with high gravel content"* (PolyMet, 2013i). This is not an appropriate use of data. Intervals with *"high gravel content"* such as this represent actual field conditions - albeit extreme- that are documented to exist at the Mine Site. They should not be excluded from the groundwater model.

Even after excluding these extreme values, the estimated hydraulic conductivity of surficial sediments in this report ranged from 2.2 ft/day to 167 ft/day (PolyMet. 2013i). Stark (1977) reported laboratory derived hydraulic conductivity values for surficial sediments just to the northeast of NorthMet that ranged from 0.4 to 362 feet per day.

These hydraulic conductivity values for surficial materials based on laboratory methods seem to be in conflict with hydraulic conductivity values presented in Table 4.2.2-5. In this table, laboratory-derived hydraulic conductivity values for reported "silty sand" are shown as ranging from 0.00043 ft/day to 0.0081 ft/day. The difference between laboratory-derived hydraulic conductivity values of up to 167 ft/day reported in PolyMet, 2013 or even higher in Stark (1977) should be reconciled with the results from a silty sand presented in Table 4.2.2-5 in the SDEIS.

It is also important to note that gravel percentages of 23 and 35 percent are not at all extreme when compared to the gravel content of many other varieties of surficial sediments known to exist in the immediate vicinity of the NorthMet Mine Site and Tailings Basin. Surficial sediments with gravel contents of greater than 60 percent are known to be present at the Mine Site (PolyMet, 2013i, Log of Boring RS-5A for example) and sediments with gravel contents ranging from 50 to greater than 80 percent are mapped in close proximity to NorthMet (Lehr, 2000, Appendix A).

While certain of these laboratory derived hydraulic conductivity values mentioned above may seem high – in the 100's – Siegel and Ericson (1980) reported hydraulic conductivities based on aquifer testing of surficial sand and gravel within the copper-nickel study area to range from 10 to 3,500 feet per day and Rainy lobe till hydraulic conductivities to range from 0.01 to 30 feet per day.

Not only are the physical properties of surficial sediment important to groundwater flow, so are their spatial arrangement.

> *"Figure 5.2.2-4 shows surficial groundwater flowpaths with the potential to transport mine-affected groundwater from identified source areas to designated evaluation locations."* (SDEIS, p. 5-33)

Figure 5.2.2-4 is a map showing the surficial groundwater flow paths at the Mine Site. This map does not show any surficial groundwater flow paths from the Mine Site to the north toward 100

Mile Swamp and Yelp Creek or to the northeast. This is unusual. It is stated elsewhere in the SDEIS, as well as being common knowledge that the elevations of groundwater surfaces in surficial sediments under unconfined conditions usually mimic surface topography.

> *"the water table is generally a subdued replica of the land surface, with groundwater divides in the Mine Site expected to roughly coincide with surface water divides"* (SDEIS, p. 4-149).

A few pages later in the SDEIS it is stated:

> *"there is a surface drainage divide oriented generally from southwest to northeast near the northern border of the Mine Site. The majority of the Mine Site, approximately 80 percent, drains south to the Partridge River through extensive wetland complexes. The remaining 20 percent of the Mine Site drains north to the One Hundred Mile Swamp and the Partridge River or northeast to the Partridge River"* (SDEIS 4-151).

It follows from these statements, in addition to well-understood geological concepts, that 20 percent of the surficial groundwater flow paths from the Mine Site should be to the north and northeast. This seems to have been ignored and should be corrected in the SDEIS groundwater modeling or it should be better explained why near-surface groundwater flow does not follow surface topography at the Mine Site. It should also be explained why Figure 2-3 in Polymet 2012s shows flowpaths from the Mine Site north to 100 Mile Swamp and Yelp Creek. This figure shows travel times of 1-5 years and 5-10 years along these flowpaths, not the travel times of thousands of years stated in the SDEIS (p. 5-33).

3.2 Surficial Geology – Tailings Basin

The level of detail presented in sections describing the surficial geology of the Tailings Basin area is minimal, not well referenced and is not based on site-specific geologic studies. The following statement made by Barr Engineering sums up their contribution to the understanding of the surficial geology of the Tailings Basin Area in support of the SDEIS. *"Site specific geologic studies of the glacial deposits have not been conducted"* (Barr 2009f). For this reason, the SDEIS must rely upon the published literature and anecdote to characterize Tailings Basin surficial geology.

One published reference the SDEIS relies heavily upon to characterize the surficial geology is Jennings and Reynolds, 2005. In fact the SDEIS' discussion of surficial geology at the Tailings Basin leads off with the following sentence.

> *"Jennings and Reynolds (2005) mapped the surficial deposits around and beneath the Tailings Basin as Rainy Lobe Till, which functions as the surficial aquifer and is generally a boulder-rich till with high clay content."* (SDEIS, p. 4-95)

A continuous layer of till with *"high clay content"* would be desirable beneath an unlined tailings impoundment. It would serve to direct groundwater to predicable locations where it could then be captured and treated. Unfortunately the quote above is entirely incorrect; the surficial Rainy lobe till in the vicinity of the Tailings Basin <u>does</u> <u>not</u> have high clay content. This claim that the Rainy lobe till has a high clay content is a direct contradiction to what is stated in multiple places the cited reference. Jennings and Reynolds (2005) clearly report the surficial Rainy lobe till they mapped in the vicinity of the proposed NorthMet project to be "clay-poor". They report Rainy lobe till matrix textures to range from 48 to 87% sand, 9 to 40% silt and 0 to 13% clay and that the matrix contains *"generally much less than 10% clay"* (Jennings and Reynolds, 2005) - this is a sandy till, not a clayey till.

The statement above further misleads the reader by not fully describing the variety of till units that Jennings and Reynolds (2005) have mapped in the vicinity of the Tailings Basin. Figure 8 shows the distribution of three different till map units in the vicinity of the Tailings Basin. The *Rainy Lobe Till* and *Water Eroded Rainy Lobe Till* map units will contain fewer layers of sand and gravel than will the third till unit mapped in the vicinity of the Tailings Basin – *Re-sedimented Rainy Lobe Till and Sorted Sediment* (Jennings and Reynolds, 2005). The later unit is a hybrid mapping unit consisting of re-sedimented Rainy lobe till and layers of sorted sand and gravel. This detail about till units demonstrates that the cited reference supports the exact opposite of the claims made in the SDEIS for the presence of *"clay-rich"* till at the Tailings Basin. The sand and gravel layers within the *Re-sedimented Rainy Lobe Till and Sorted Sediment* unit will provide significant pathways for groundwater flow and contaminant transport at the Tailings Basin as well as at the Mine Site.

The following sentence seems to downplay the significance of outwash at the Tailings Basin.

> *"The area farther northwest of the Tailings Basin is believed to be one of the few areas in the region with significant quantities of outwash (sand and gravel) and thicknesses ranging from 0 ft to greater than 150 ft (Olcott and Siegel 1979) (see Figure 4.2.2-12)."* (SDEIS, p. 4-95)

The mention here of significant quantities of outwash sand and gravel occurring some unspecified distance *"farther northwest of the Tailings Basin"* is irrelevant to the geology of the Tailings Basin site. The SDEIS does not cite references that may allow for a more accurate characterization of the surficial geology of the Tailings Basin site. A large-scale existing surficial geologic map (Lehr, 2000) shows outwash sand and gravel mapped beneath the northeastern portion of the Tailings Basin and shows mapping units that potentially contain large amounts of sand and gravel occurring between the Tailings Basin and the Embarrass River and Heikkila Lake (Figure 9) down hydraulic gradient. Seeps are known to exist along the north side of the Tailings Basin (Barr, 2007g, Figure 6) where taconite tailings have been placed over this area of outwash. Subsurface data also exist to confirm the presence and define the thickness of this sub tailings basin outwash sand and gravel. RS-27 and RS-28 were drilled along the north margin of Cell 2E (Barr, 2009e) in the vicinity of seeps (Barr, 2007g). These two drill holes show 25 feet and 21.5 feet of outwash sand and gravel to be present beneath a 5 to 6 foot thick interval of taconite tailings fill. In both of these holes the outwash sand and gravel immediately overlies Giants Range granite (Barr, 2009e) resulting in the lack of any hydrologic barrier separating bedrock from sand saturated with process water. The locations of these seeps would be predicted based on the presence of outwash beneath the tailings pile.

Jennings and Reynolds (2005) mapped a Rainy lobe ice margin extending through the Tailings Basin and mapped the hybrid till/sand and gravel mapping unit both to the east of the Tailings Basin and between the Tailings Basin and Heikkila Lake (Figure 8). To better understand the site, I prepared additional glacial geomorphology maps using the U.S. Geological Survey 7.5 minute topographic maps published in 1949 before construction of the Tailings Basin. These maps indicate multiple ice-marginal pitted outwash fans beneath the northern portions of the Tailings Basin (Figure 10; Figure

11). These recently mapped ice margins beneath the Tailings Basin are in alignment with other representations of Rainy lobe ice margins that have been mapped both north and south of the Tailings Basin previously (Figure 8; Figure 9) (Lehr, 2000; Lehr and Hobbs, 1992; Jennings and Reynolds, 2005). More recent photo revisions of quadrangles covering the northeastern part of the Tailings Basin (specifically the Isaac Lake and Allen 7.5 minute quadrangles) from the 1960's and 1980's show three gravel pits covering at least 30 acres within this area now inundated by tailings. Many sources of information indicate significant quantities of outwash sand and gravel to be present beneath and in close proximity to the Tailings Basin.

The hydrologic significance of these areas of outwash beneath the Tailings Basin relates to their potentially extreme hydraulic conductivities - 10 to 3,500 feet per day based on local studies (Siegel and Ericson (1980). Layers of outwash of practically any scale would promote the rapid movement of groundwater from beneath the tailings pile and beyond, especially considering the high heads created with the upward vertical expansion of the tailings pile. Some of this groundwater flow would emerge at the base of the tailings pile as seeps and some would flow beyond as groundwater. The SDEIS' assumptions that nearly all Tailings Basin groundwater can be effectively captured and treated are based on a very incomplete understanding of the geology of the Tailings Basin site.

The design of any engineered solution to capture and treat groundwater flow emanating from the Tailings Basin must take into account the three-dimensional occurrence of outwash sand and gravel bodies as well as bedrock fractures present beneath and surrounding the Tailings Basin and must also consider the pre-Tailings Basin surface water flow directions as well because groundwater within these areas likely still flows in those historic directions. This has not been done in the SDEIS.

4.0 GENERAL BEDROCK GEOLOGY

A few general comments related to bedrock geology presented in the SDEIS are presented below. In general the presentation of bedrock geology within the SDEIS is weakly referenced and not entirely accurate, which undermines scientific credibility.

The claim is made on page 4-43 that the all three mine pits will retain a specific and predictable separation from the Biwabik Iron Formation – hydrologic separation as well as spatial separation. This claim is crucial to safeguard the water quality of one of the region's most important bedrock aquifers. The SDEIS' claim of hydrologic separation from the Biwabik Iron Formation aquifer should be supported by a more robust reference than personal communication from one of PolyMet's consultants. The SDEIS should include an accurate geologic cross-section based on actual drilling information, showing the locations of faults and fractures, not a schematic or overly generalized cross-section where subsurface conditions can be so easily misrepresented.

The discussion on page 4-43 describing the relationship between rocks of the Duluth Complex and older rock to the north does not fully convey the important relationship between the Duluth Complex rocks and the older rocks to the north. The Duluth Complex in the vicinity of NorthMet intrudes the argillaceous rocks of the Virginia Formation (the "footwall of the deposit"). This is not a trivial point because the Virginia Formation is responsible for supplying the sulfur to the ore deposit and because contact metamorphosed Virginia Formation in the footwall and inclusions represent some of the most reactive waste rock that will be encountered. An in-depth understanding of relationships that exist between the ore deposit, footwall rocks and metamorphosed Virginia Formation inclusions is necessary for accurate management of reactive waste rock.

The examples of incorrect usage of geologic terminology in the SDEIS below suggest the sections on geology were not given the level of editorial review appropriate for a scientific publication.

> *"The NorthMet Deposit itself is below the surficial till in the layered mafic intrusive rocks of the Duluth Complex, which are part of the Partridge River intrusion."* (SDEIS, p. 4-43)

Actually the Duluth Complex is <u>not</u> part of the Partridge River intrusion. The Partridge River intrusion is part of the Duluth Complex.

> *"The oldest of the sedimentary rocks is the Pokegama Quartzite. These sedimentary rocks are underlain by Archean granite of the Giants Ridge batholith."* (SDEIS, p 4-43)

The correct terminology is Giants <u>Range</u> batholith, not Giants <u>Ridge</u> batholith. This same incorrect usage is repeated in several additional places on pages 4-94 to 4-95.

5.0 POTENTIAL FOR HYDROLOGIC CONNECTIONS BETWEEN SURFICIAL AND BEDROCK AQUIFERS

The nature of the interaction between surface water, groundwater in surficial aquifers and groundwater in bedrock aquifers in the natural environment is directly related to the spatial arrangement of the various surficial sediments, their spatial relationship to the bedrock surface and the nature of fractures in the bedrock. When these spatial relationships are well understood, and inputs to computer models represent actual field conditions, computer models will more accurately predict actual outcomes. Several separate areas within the SDEIS touch upon the subject of hydrologic interconnectivity, and there are several instances of conflicting information.

The claim that there is little connection between water in the bedrock aquifer, water in the surficial aquifer and surface water is made in several places within the SDEIS. In some places these claims may be supported by data; in other places they are not.

> *"Hydraulic analyses, however, indicate that the hydraulic connection between surficial aquifer and underlying bedrock underlying is weak. Water-table monitoring during a 30-day pumping test at bedrock well P-2 showed a small amount of drawdown in the nearest deep wetland piezometer, but no detectable drawdown at other water table or deep wetland piezometers (PolyMet 2013i; Barr 2007b)."* (SDEIS, p. 4-47)

> *"Because of the general lack of interaction between the surficial and bedrock aquifers, the hydrology of many wetlands at the Mine Site is primarily supported by direct precipitation with some variable surficial groundwater components from the uplands. Organic and mineral soils at the Mine Site are typically perched over the dense till or a local sandy textured surficial aquifer, resulting in perched wetlands."* (SDEIS, p. 4-149)

The nature of the interaction between the surficial aquifer and the bedrock aquifer is an important subject that directly relates to the ability to accurately predict the movement of ground water and contaminants and also to the ability to predict the impacts of mine dewatering on surface waters such as wetlands and streams.

A very simplistic conceptual model of homogeneous surficial geology might provide confidence that a single pump test for 30 days would confidently prove the inferred weak hydrologic connection between bedrock and surficial sediments. However, all of the data cited previously suggests that the surficial geology is heterogeneous, so groundwater flow will be more complex than can be measured with a single pump test. Incidentally, the fact that the bedrock pumping well in this pump test (P2) could be pumped for 30 days implies a constant supply of water flowed to the pump through interconnected hydrologic pathways.

Without data in the body of the SDEIS to support the claim that a single pump test could lead to such an unequivocal conclusion, the reviewer is forced to search for additional tables, maps or cross-sections that could support the claim that the connection between the surficial aquifer and groundwater is "weak". PolyMet, 2013i, is a 2,870 page document and Barr (2007b) is 293 pages long. This same claim of a weak connection between the bedrock, unconsolidated deposits and wetlands based on this same single pump test is presented again on page 4-150.

> "*Because of the low permeability of the bedrock, the interaction between the surficial deposits and the bedrock aquifers is assumed to be insignificant, according to Siegel and Ericson (1980) (Barr 2010d).* " (SDEIS, p. 4-149)

The statement that the interaction between surficial deposits and bedrock is "insignificant" is not supported by Siegel and Ericson (1980). Actually they stated the opposite. According to them *"near the surface, water in bedrock fractures and joints is hydraulically connected with overlying surficial aquifers" (*Siegel and Ericson, 1980, p. 7). Other hydrologic studies carried out in the immediate NorthMet area contemporaneously with Siegel and Ericson reached the same conclusion. Stark (1977) reported *"surficial materials and bedrock aquifers appear to be in full hydrologic connection. Flowpaths in the Duluth Complex are dependent on joint patterns."* (p. 71) Stark (1977) concluded that *"because of their coarse texture, surficial aquifers could easily become polluted. Fractures in the Duluth Complex may have the ability to serve as flow channels from polluted areas to surface waters."* (p. 85)

Other paragraphs in the SDEIS acknowledge a connection between wetlands and adjacent unconsolidated deposits dependent on hydraulic conductivity.

> "*The degree of hydraulic connection between the wetland areas and adjacent unconsolidated deposits and bedrock at the Mine Site is expected to be variable, depending on the characteristics of the wetlands and the localized hydraulic conductivity and degree of bedrock fracturing.*" (SDEIS, p. 4-150)
>
> *There are some wetlands located within the Plant Site and saturated conditions generally exist less than 10 ft below the ground surface, like the Mine Site. Similar to the Mine Site, the degree of hydraulic connection between the wetland areas and adjacent unconsolidated*

> *deposits and bedrock at the Plant Site is expected to be variable, depending on the characteristics of the wetlands and the localized hydraulic conductivity and degree of bedrock fracturing. Given the very low hydraulic conductivity of the underlying bedrock, there is minimal potential for hydraulic connection between bedrock and wetlands."* (SDEIS, p. 4-165)

These quotes recognize that the degree of hydraulic connection between wetlands and adjacent unconsolidated deposits and bedrock at the mine site is related to hydraulic conductivity and the degree of bedrock fracturing. Contradictory claims in the SDEIS that there is insignificant connection between surficial aquifers and bedrock aquifers must be resolved. Although surficial materials and bedrock may be isolated in some locations, it is likely that there would be significant interaction between ground water in surficial materials and bedrock especially along the lateral trends of bedrock lineaments.

Field measurements also support a hydraulic connection between surficial sediments and bedrock.

> *"Water table elevations measured by PolyMet in Mine Site bedrock boreholes indicate that the hydraulic gradient is similar to that of the overlying alluvium (sloping down to the south and southeast across the Mine Site), consistent with a hydraulic connection between the alluvium and bedrock units (PolyMet 2013i)."* (SDEIS, p. 4-46)

Probably most convincing argument of a hydrologic connection between the surface and bedrock aquifers comes from water quality data from bedrock wells.

> *"The presence of ammonia nitrogen in the samples likely indicates that there is a hydraulic connection between the bedrock aquifer and the surficial aquifer, however the nature of this connection cannot be determined at this time"* (Barr, 2006b).

It has been suggested that the source of this ammonia in the bedrock aquifer is from unoxidized blasting emulsion used in the Peter Mitchell Mine to the north. The presence of ammonia in deep groundwater from the Mine Site is difficult to explain other than as surface contamination traveling deep into the bedrock groundwater system.

6.0 OTHER COMMENTS

6.1 Use of Waste Rock and Overburden as Construction Aggregate

PolyMet intends to use waste rock and overburden from the NorthMet deposit as well as 1,000,000 cubic yards of waste rock from a state-owned taconite stockpile located approximately five miles west of the Mine Site, adjacent to Dunka Road (Desautels and Zurowski, 2012) for various construction uses at NorthMet. The estimated construction aggregate needs for the project are huge. Golder Associates (2007) reports waste rock quantities required for the following uses: in-pit haul roads – 10 million tons, stockpile foundations - 20 million tons, pit access roads – 0.7 million tons and rail transfer hopper platform – 0.6 million tons. Risks surrounding the use of these materials for construction should their characterization be inaccurate are two-fold; 1) human health risks associated with the occurrence of fibrous amphibole minerals and 2) risks related to water quality, specifically acid rock drainage and mobilization of metals.

Due to the unresolved health concerns surrounding the occurrence of fibrous amphibole minerals in rocks such as those at Dunka and NorthMet, the Minnesota Department of Transportation (MnDOT) has a long-established policy prohibiting the use of rock materials from mines east of a line near Biwabik as construction aggregate on state projects. MnDOT's policy would preclude use of Dunka and NorthMet materials for construction. However, MnDOT's jurisdiction only covers use of these materials in MnDOT right-of-way or state-aid projects. Other agencies would determine whether materials from NorthMet could be used in construction (Charles Howe, Geologist Supervisor, MnDOT, personal communication, January 27, 2014).

Assuming that the only approval required for use of this controversial aggregate material would be that of MDNR, which may collect over $500,000 from the transaction (Desautels and Zurowski, 2012, Table 21-4), the question remains is safe use of these materials in construction supported by science? The SDEIS does not disclose that the use of these materials conflicts with MnDOT's (the State's) policy excluding use of these materials. Health risks surrounding fibrous amphibole mineral exposure should be evaluated before Dunka or NorthMet materials are used for construction.

The sulfur content of Dunka waste rock proposed to be used as aggregate is also an issue because waste rock stockpiles at Dunka are currently producing acid drainage. This concern also applies to NorthMet waste rock. A report contained in the supplementary references to the SDEIS addresses the potential reactivity of sulfur-bearing waste rock from NorthMet, specifically where waste rock is spread thin as in surfacing haul roads and mine access roads.

> "*The concept of "non-reactive" waste rock cannot be defined when drainage from waste rock is required to meet stringent water quality discharge limits. Even thin waste rock placement containing low levels of sulfide mineralization may produce drainage chemistry exceeding the limit for copper (in particular) because the water quality standards are hardness based and result in low water quality discharge limits." (SRK, 2007b, p. 98)*

PolyMet also intends to use peat and unsaturated overburden for construction and reclamation. These materials will be stored in unlined stockpiles (SDEIS, p. 3-44). As discussed previously, unsaturated overburden may generate acid or leach metals. It is suggested that, unless specific data demonstrates otherwise, all overburden at NorthMet should be managed as reactive with the potential to leach metals. Stockpiles of overburden and peat should be placed above geomembrane liners with leachate collection systems and neither should be used in construction.

6.2 Waste Rock Characterization

There seems to be a contradiction in the definition of reactive waste rock contained in the SDEIS and what is defined in some of the supporting technical materials.

> *" in rock with less than 0.12 percent sulfur (S), the oxidation rate is slow enough that all acid produced during weathering would be completely neutralized by reaction with silicate minerals, so this low-sulfur rock (classified at Category 1 waste rock in the NorthMet Project Proposed Action) is predicted to never generate acidic leachate"* (SDEIS, p. 5-51)

The statement above conflicts with a report by SRK (2007b) that is cited in the SDEIS where it is stated that *"the MDNR and PolyMet agreed … 'non-reactive' waste rock was defined as rock with less than or equal to 0.05% sulfur"* (p. 23). This SRK report further states that "*the reactive category (> 0.05% S) was expected to include rock that may or may not generate ARD but regardless would leach metals at a level that would not meet water quality discharge standards"* (SRK, 2007b, p. 23). The 2007 SRK report seems to rely upon the MDNR's long-term acid mine drainage research program, which apparently defined reactive waste rock as rock with more than 0.05% sulfur. It is unclear from reading the SDEIS how this agreed-upon definition changed into the SDEIS threshold of 0.12% sulfur -- allowing Category 1 waste rock to be placed in an unlined stockpile. Even if rock with between 0.05% sulfur and 0.12% sulfur may not generate acid, it will leach metals at levels that would not meet water quality discharge standards (SRK, 2007b). Any reactive rock, as defined in the SRK report and the MDNR's acid mine drainage research program, should only be stored above geomembrane liners with leachate collection systems.

6.3 Cumulative Impacts

There are a number of indications that PolyMet intends to expand once initial permits are secured. Their own Technical Report (Desautels and Zurowski, 2012, p. 20-10) geared towards securities regulators and investors as well as a stock research report (Edison Investment Research, 2013) recently commissioned by PolyMet discusses these plans. The plans for expansion change the potential for negative environmental effects; therefore these plans should be discussed as part of this EIS process.

The Edison report suggests that the most probable and near-term expansion at NorthMet would be to increase daily production at the processing plant. It is well known that the old LTVSMC plant has a daily capacity to process approximately 100,000 tons. According to the SDEIS PolyMet is proposing to mine, crush and process only 32,000 tons per day. The Edison report states that PolyMet intends to initiate a new permit process to allow for this expansion within the first six months of operations (Edison Investment Research, 2013, p. 12). This level of expanded production has a direct bearing on the ability of the LTVSMC tailings basin to accept additional tailings and whether engineered systems to capture and treat the seepage water are adequate.

As is common with other open-pit copper mines, NorthMet could expand to an underground operation (Fiscor, 2010) once the ore economically accessible through surface mining becomes depleted, or possibly synchronous with open pit mining if metal prices would allow.

PolyMet's current technical report (Desautels and Zurowski, 2012) defines 694 million short tons of indicated and measured resources and 230 million tons of inferred resources or a total of 924 million tons of ore that meets their accepted grade within their current lease holdings at NorthMet (p. 14-38). This volume of resources is defined based on certain cutoff values for metal percentages contained in the rock and assumed market prices for finished metals.

With nearly a billion tons of resources, PolyMet could be mining at NorthMet for far longer than 20 years. The Proposed Action's pit layout captures approximately 20 years of the highest grade reserves that exist within reach of open-pit mining methods. This defines what the report calls the DFS pit shell. The technical report defines 118 million tons of proven reserves and 157 million tons of probable reserves for a total of 275 million tons within the DFS pit shell (Desautels and Zurowski, 2012, p. 25-3). In the SDEIS, PolyMet proposes mining 225 million tons over 20 years.

If NorthMet were to operate as proposed, at the end of 20 years of mining there could be 650 to 700 million tons of resources remaining. This number could grow larger if metal prices increase and/or metal recovery technologies improve and/or additional drilling and assaying occurs. This issue has bearing on probably cumulative effects of the project and should be analyzed as part of a revised EIS.

Lastly, the SDEIS seems not to take into consideration the numerous other Cu-Ni-PGE deposits and Ti deposits that are known to exist in the immediate vicinity of NorthMet. Most of the following deposits have 43-101-compliant resource estimates prepared and some are in the pre-feasibility stage: Twin Metals Spruce Road, Maturi and Birch Lake deposits, Cardero's Longnose and Titac deposits, Teck America's Mesaba deposit and Encampment Minerals' various deposits (MDNR, 2013). It is well-known that these companies are poised to begin environmental review should the NorthMet Proposed Action receive approvals. The cumulative environmental effects of these projects should be addressed in a revised EIS.

7.0 CONCLUSIONS

Many sections of the SDEIS dealing with geology have serious omissions where scientific data should have been provided. The scientific credibility of the SDEIS is further compromised by numerous instances where cited references are misquoted and other areas where important assumptions made about geology and hydrogeology are unsupported. The scientific credibility of the SDEIS could be improved by the use of more current references and a more accurate representation of what is stated in the references. In addition, the presentation of data tables, geologic cross-sections and maps in support of key assumptions would greatly improve the scientific credibility of many sections of the SDEIS.

As mentioned in numerous places in this review, an understanding of surficial geology is crucial to the ability to accurately predict groundwater flow and contaminant transport. Considering the amount of effort – both time and resources -- invested into the EIS process, preparation of a site-specific surficial geologic map and multiple geologic cross-sections showing the relationship between the full range of surficial sediments and the bedrock surface would have been relatively simple and inexpensive. The payoff seems especially high considering that the result of a thorough understanding of the three-dimensional distribution of surficial sediments across the project site would be the ability to more accurately and more confidently predict groundwater and contaminant flow. PolyMet seems to be planning to conduct an extensive geotechnical drilling program – 480 holes – should the Final EIS be approved (Desautels and Zurowski, 2012). If this drilling would have been carried out during the environmental review process, significantly more detail on the distribution and physiochemical properties of surficial sediments would be available allowing for more accurate mapping of conduits for groundwater and contaminant flow.

The subject of bedrock fracturing should have received much greater attention in the SDEIS. Considering the significance of fractured bedrock to groundwater flow and the potential to transport contaminants long distances or to nearby salient ecosystems, considerably more effort should have been directed at studying the hydrologic significance of bedrock fractures that exist at both the NorthMet Mine Site and the Tailings Basin site. Just presenting the entire RQD dataset would have provided significantly more information about the spatial distribution of bedrock fractures at the NorthMet site than is presented in the SDEIS. To evaluate the potential significance of bedrock fracturing and accurately predict groundwater flow and contaminant transport, field studies of bedrock fractures at the NorthMet Mine Site and the Tailings Basin site should have also been undertaken.

The use of average hydraulic conductivity values for surficial sediments or bedrock is also problematic. Averaging individual hydraulic conductivities removes the range of data that represent actual field conditions. In one instance reported above, data showing higher hydraulic conductivity were actually deleted from the dataset used to calibrate the MODFLOW model, and then average values were calculated. Areas of higher hydraulic conductivity in surficial sediments, such as outwash, and bedrock fractures may represent conduits through which contaminated groundwater will migrate. By eliminating these extreme values from groundwater model inputs, one essentially eliminates from the model the most likely pathways for contaminant transport. By ignoring high hydraulic conductivity pathways in the NorthMet groundwater model, the equivalent of an interstate highway option for contaminant travel has been eliminated from consideration.

A more careful evaluation of bedrock and surficial geology raises concerns about the assumptions for leachate collection and containment in the SDEIS, the proposed use of reactive materials in construction, and the storage of reactive materials in unlined stockpiles. Analyzing geology on a more rigorous basis would suggest greater connectivity between surficial and bedrock groundwater, potentially affecting predictions of wetlands impacts as well as the pathways for acid drainage and mobilized metals. With a project of this nature, weaknesses in the geologic data and analysis undermine many key assumptions and conclusions regarding the project and its potential impacts.

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Note: For references cited in the SDEIS, the letter following the year represents the same letter designator used in the SDEIS list of references

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J.D. Lehr provides independent geological consulting and expert witness services, including identification, characterization and quantification of construction aggregate resources and research, mapping and database services to assist clients in the areas of strategic business planning, mineral resource acquisition and valuation, mine planning, permitting and environmental review.

1997 to 2004 - Aggregate Industries, Inc. (Regional Geologist, Senior Geologist)
Managed the company's aggregate reserves exploration and evaluation program both for secured properties and potential acquisition properties. Provided geologic, GIS and GPS expertise for mine permitting, mine planning, environmental review for mining projects, strategic business planning, mine operations, sales and marketing and aggregate quality control.

1988 to 1997 - Minnesota Department of Natural Resources (Research Scientist 2 - Surficial Geology)
Managed and conducted the Minerals Division's program to map surficial geology and construction aggregate resource potential of certain Minnesota counties. Evaluated aggregate resource potential of state lands and county tax-forfeited lands proposed for sale or exchange and contributing expertise in the areas of aggregate resources, other industrial minerals, glacial geology and remote sensing to other units within the DNR.

1986 to 1988 - South Dakota Geological Survey (Geologist 1, Geologist 2)
Managed and conducted county geologic studies of glacial drift and bedrock in support of U.S. Geological Survey county hydrologic studies. Tasks included geologic mapping of glacial sediments and bedrock, extensive drilling, borehole geophysical logging, and preparation of drilling logs, geologic cross-sections and geologic maps.

1984 to 1986 - University of Minnesota – Duluth (Teaching Assistant, Research Assistant)
Taught undergraduate geology laboratory classes. Prepared rock samples and thin sections for faculty research projects.

EDUCATION

Master of Science Degree - Geology - University of Minnesota (2000)
Thesis Title: *The Pleistocene Geology of the Embarrass Area, St. Louis County, Minnesota*
Graduate studies in geology - University of Minnesota, Duluth (1984-1986)
Graduate studies in geology - University of Iowa (1983-1984)
Bachelor of Science Degree - Soils, Earth Science Option - North Dakota State University (1982)
Undergraduate studies in geology - North Dakota State University (1979-1982)
Undergraduate studies in liberal arts - Concordia College, Moorhead (1977-1979)

LICENSES AND CERTIFICATIONS

Licensed Professional Geologist No. 30063, Minnesota
Certified Professional Geologist No. 10267, American Institute of Professional Geologists

OTHER PROFESSIONAL ACTIVITIES

Mapping of surficial geology in northeastern Minnesota (2010-2014)

Instructor at North House Folk School, Grand Marais, Minnesota - prepared and taught "The Geology of North Shore Eskers" (2012)

Chair of Minnesota Geological Survey Geologic Mapping Advisory Committee (2006)

Co-organizer of 2005 Minnesota Section of AIPG Fall Geology Field Trip

Co-organizer of Minnesota Aggregate Mining Conferences held in St. Cloud in 2003 and 2005

Invited presentation at U.S. Geological Survey-sponsored workshop on applied Quaternary geology mapping, Bloomington, Indiana (1993)

Organized and led the 1992 Midwest Friends of the Pleistocene Field Conference in northeastern Minnesota

Organized 1991 a regional Workshop on Midwestern Quaternary geology mapping techniques

PUBLICATIONS

Lehr, J.D., 2000, The Pleistocene geology of the Embarrass area, St. Louis County, Minnesota: Minneapolis, University of Minnesota, 157 p., map scale 1:48,000.

Mooers, H.D., Ojakangas, R.W., Donaldson, J.A., Prest, V., and **Lehr, J.D.**, 1999, On the dispersal of Belcher Island erratics into the western Lake Superior region: *Geological Society of America Abstracts with Program.*

Mooers, H.D., and **Lehr, J.D.**, 1998, Terrestrial record of Laurentide Ice Sheet reorganization during Heinrich events, Comments and Reply: *Geology*, v. 26, no. 7, p. 666-669.

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Nelson, S.L., Lawler, T.L., **Lehr, J.D.**, Theobald, P.K., Ryder, J.L., Sutley, S., and Tripp, R., 1994, Heavy minerals from glaciofluvial sediments in Minnesota: Institute on Lake Superior Geology, 40th Annual Meeting, Proceedings, Part 1, Program and Abstracts, v. 40, p. 48-49.

Lehr, J.D., 1993, Minnesota's aggregate mapping program: *Applied Quaternary Research: Canadian Quaternary Association Program with Abstracts and Field Guide*, p. A28.

Lehr, J.D., 1993, Sand and gravel resources, in A compendium of mineral resource information, east-central Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 313, p. 15-19.

Meyer, G.N., Patterson, C.J., Hobbs, H.C., and **Lehr, J.D.**, 1993, Surficial geology, in Meyer, G.N., and Falteisek, J., eds., Regional Hydrologic Assessment - Anoka, Chisago, Isanti, and Sherburne Counties, Minnesota: Minnesota Department of Natural Resources, Division of Waters RHA-1, map scale 1:200,000.

Lehr, J.D., 1992, Aggregate resources and Quaternary geology of Isanti County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals, map scale 1:100,000.

Lehr, J.D., 1992, Minnesota's aggregate mapping program, in Sidder, G.B., Sims, P.K., Chadima, S., and Biek, R.F., eds., Industrial Minerals - Today and Tomorrow: The Raw Materials to Build the Upper Midwest: U.S. Geological Survey Open-File Report 92-514, p. 31-32.

Lehr, J.D., and Hobbs, H.C., 1992, Field trip guidebook for the glacial geology of the Laurentian divide area, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Guidebook Series No. 18, 73 p., map scale 1:250,000.

Lehr, J.D., 1991, Aggregate resources and Quaternary geology of Wright County, Minnesota: Minnesota Department of Natural Resources, Division of Minerals Report 294, 18 p. text, map scale 1:100,000.

Mooers, H.D., **Lehr, J.D.**, Hobbs, H.C., and Gilbertson, J.P., 1991, Correlation of late Wisconsin ice margins in Minnesota: *Geological Society of America, Abstracts with Programs,* v. 23, no.3, p. 50.

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Gilbertson, J.P., Duchossois, G.E., Hammond, R.H., **Lehr, J.D.**, and Tomhave, D.W., 1987, Pleistocene geology of eastern South Dakota, U.S.A.: *International Union for Quaternary Research XII International Congress, Program with Abstracts*, p. 173.

List of Figures (attached separately)

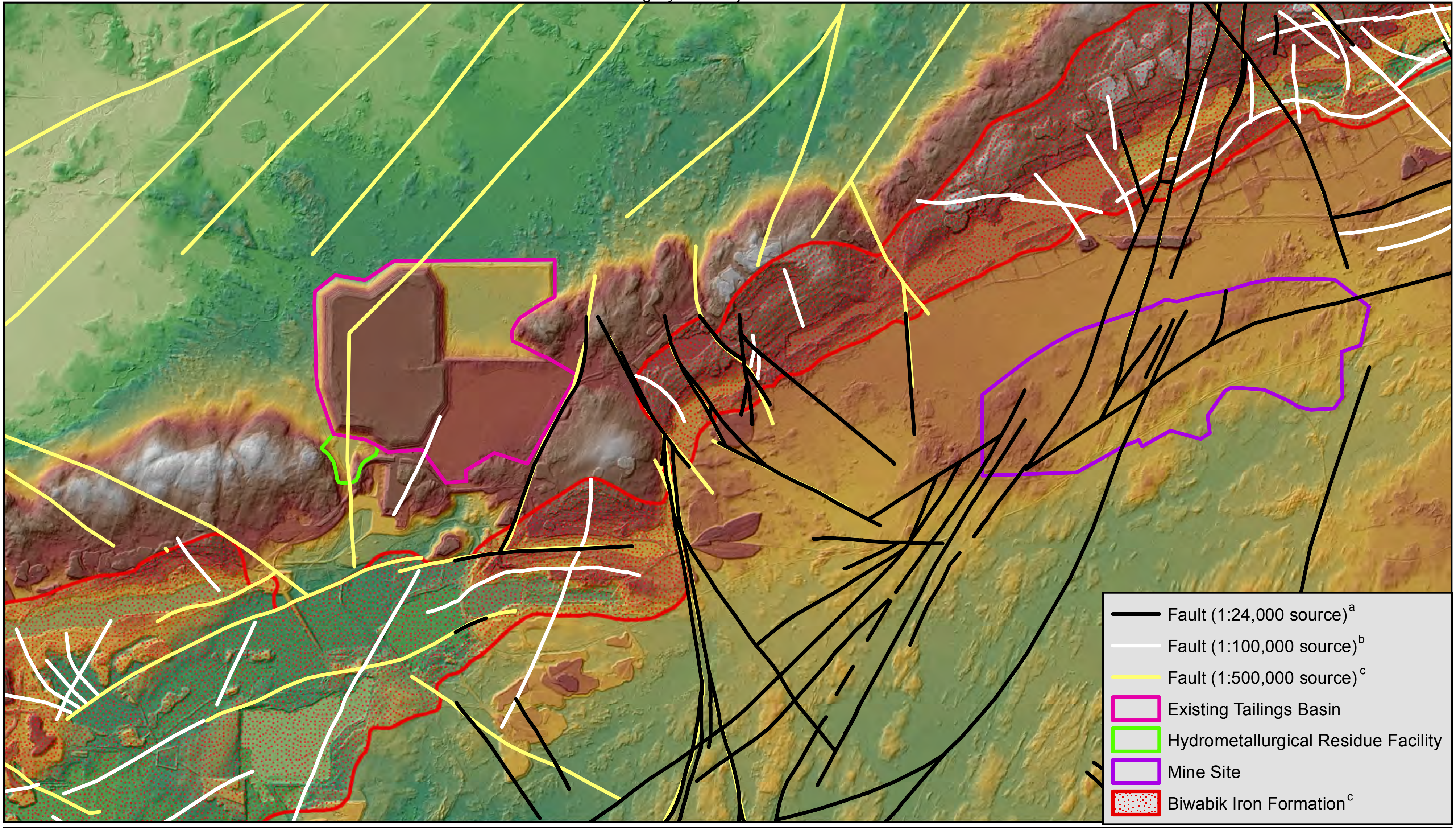


FIGURE 1

FAULTED BEDROCK AND SURFACE TOPOGRAPHY VICINITY OF PROPOSED NORTHMET COPPER MINE

ST. LOUIS COUNTY, MINNESOTA

data sources

[a] Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geology of the Allen quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-091, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt quadrangle, St. Louis and Lake counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-159, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt northeast quadrangle, St. Louis and Lake counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-160, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt southwest quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, M-161, scale, 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt southeast quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-162, scale 1:24,000.
[b] Jirsa, M.A., Chandler, V.W., and Lively, R.S., 2005, Bedrock geology of the Mesabi Range: Minnesota Geological Survey Miscellaneous Map Series M-163, scale 1:100,000.
[c] Jirsa, M.A., Boerboom, T.J., Chandler, V.W., Mossler, J.H., Runkel, A.C., and Setterholm, D.R., 2011, Bedrock geologic map of Minnesota: Minnesota Geological Survey State Map Series S-21, scale 1:500,000.
Background LiDAR topography images from Minnesota Geospatial Information Office

February 19, 2014

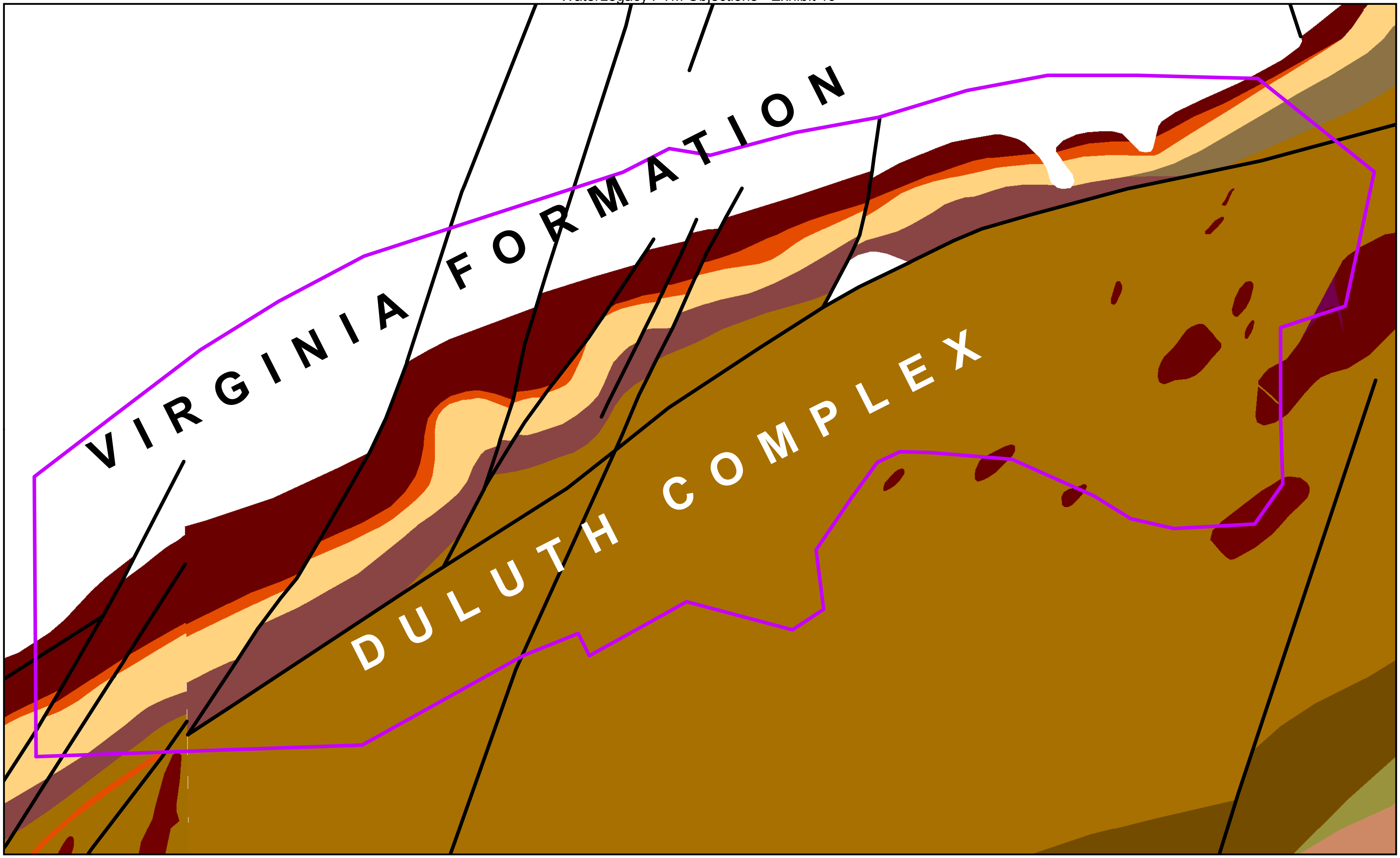


FIGURE 2

BEDROCK GEOLOGY
VICINITY OF PROPOSED NORTHMET COPPER MINE
ST. LOUIS COUNTY, MINNESOTA

Data Source:

Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geology of the Allen quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-091, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt quadrangle, St. Louis and Lake counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-159, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt northeast quadrangle, St. Louis and Lake counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-160, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt southwest quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, M-161, scale, 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt southeast quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-162, scale 1:24,000.

February 19, 2014

Pickup truck cab for scale

FIGURE 3 – Photos of Bouldery Rainy Lobe Till at Peter Mitchell Mine

Data source: Supplemental materials included with Jennings, C.E. and Reynolds, W.K., 2005, Surficial geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-164, scale 1:100,000.

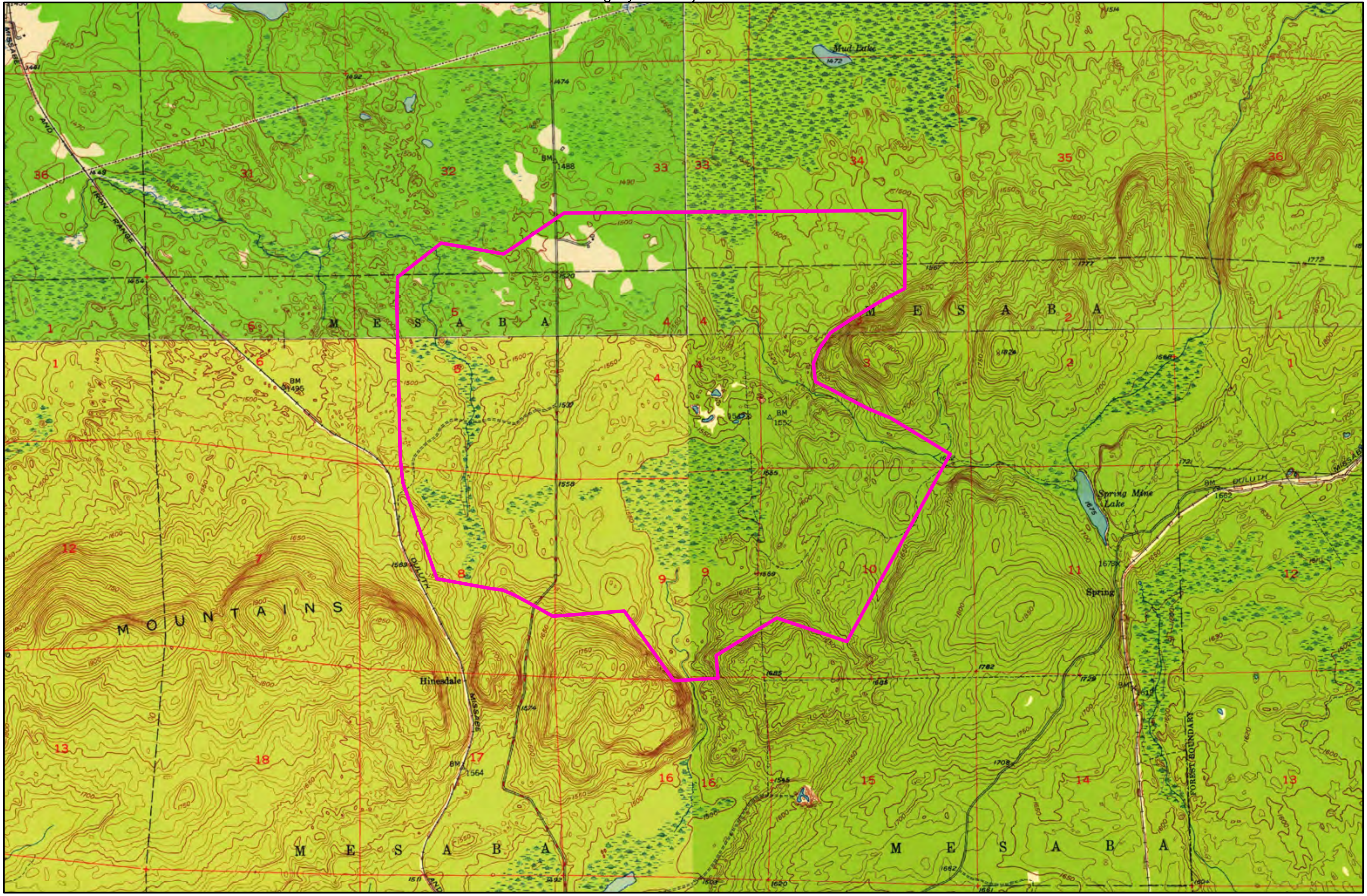


FIGURE 4

HISTORIC USGS QUADRANGLE MAPS VICINITY OF LTVSMC TAILINGS BASIN

ST. LOUIS COUNTY, MINNESOTA

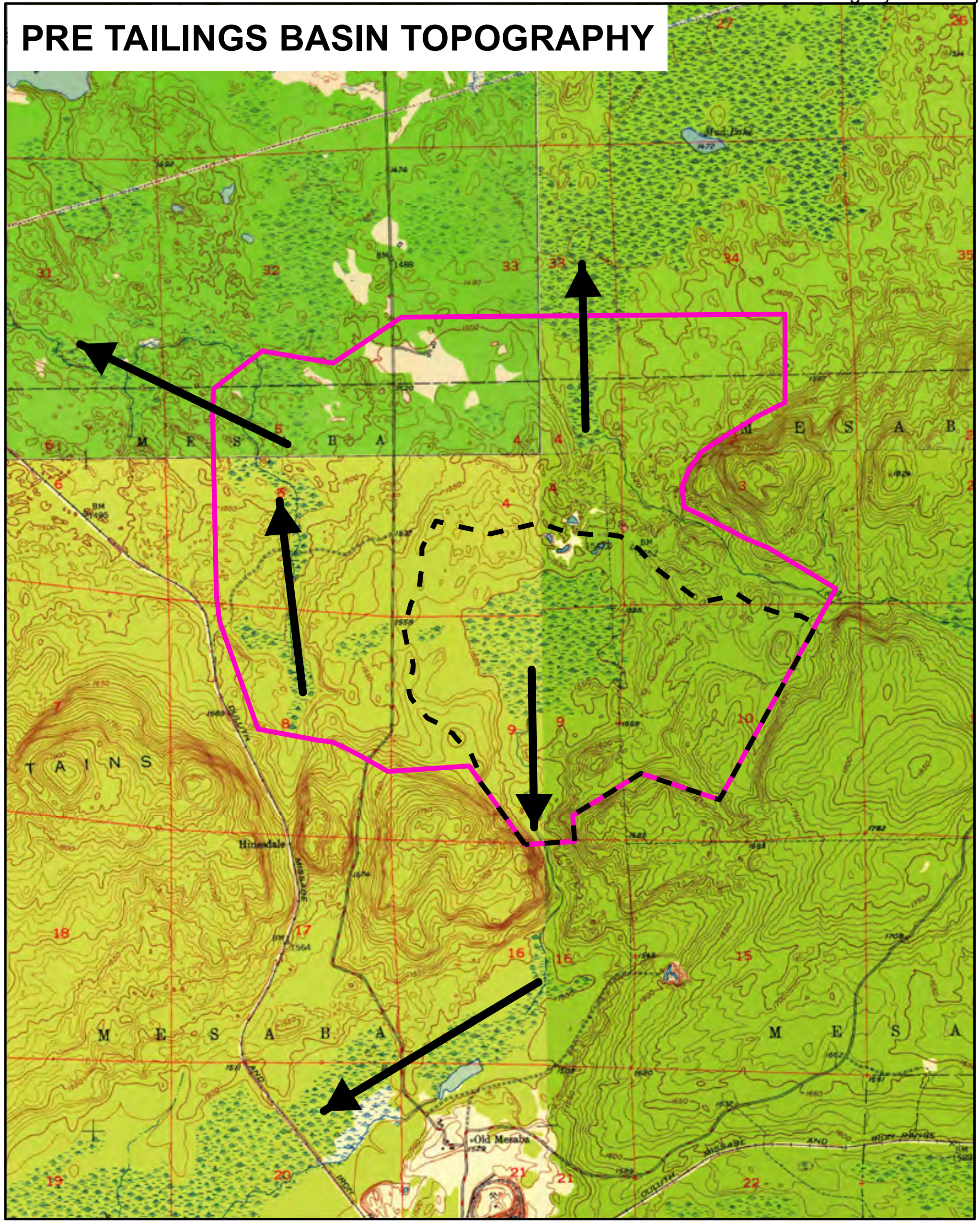
0 0.5 1 Miles

Legend

Existing Tailings Basin (2,900 acres total)

Data Source:
U.S. Geological Survey 7.5 minute series: Embarrass, Isaac Lake, Aurora and Allen quadrangles
Published 1949 - Based on 1947 air photos

February 19, 2014



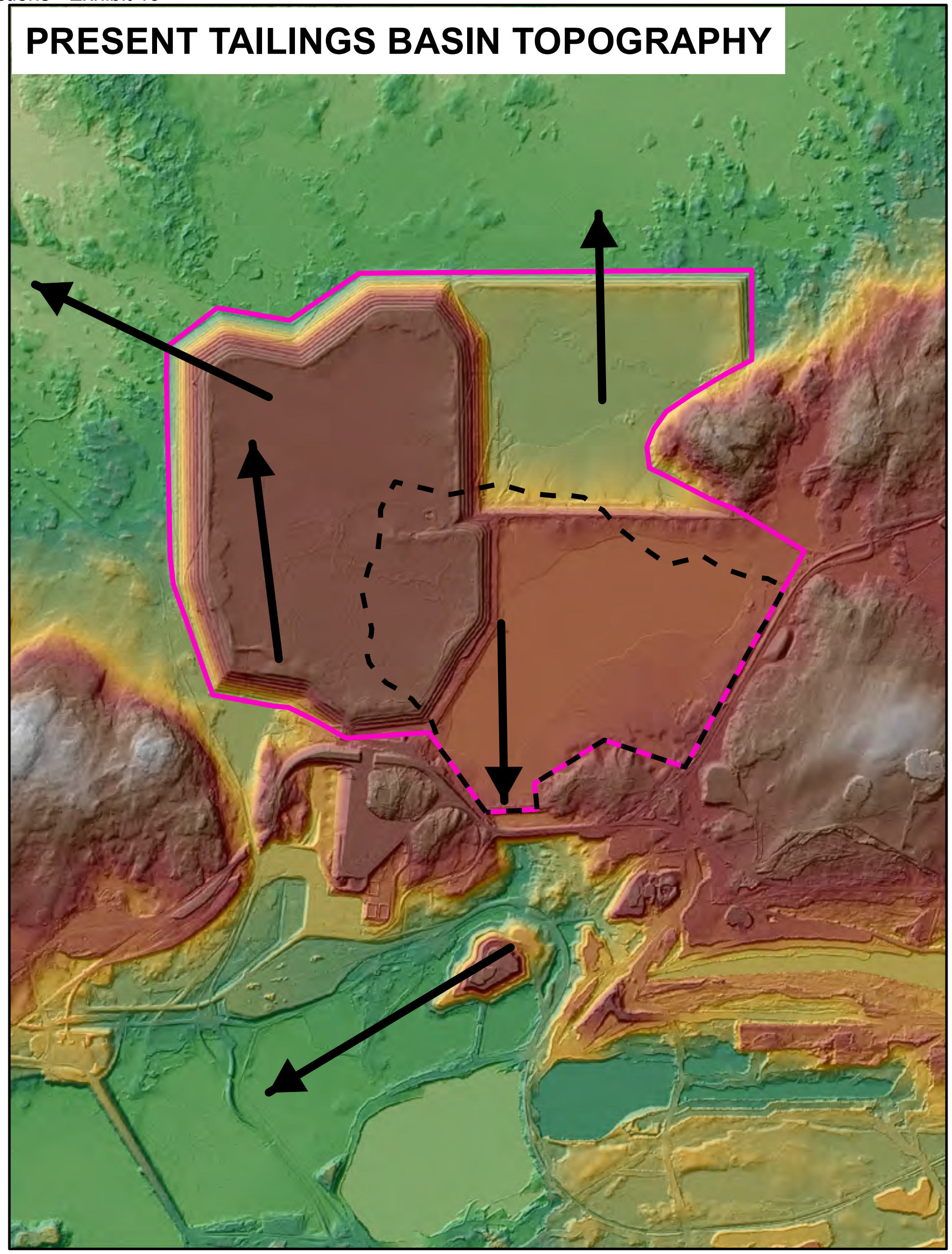


FIGURE 5

ORIGINAL SURFACE DRAINAGE AND CURRENT TOPOGRAPHY
VICINITY OF LTVSMC TAILINGS BASIN

ST. LOUIS COUNTY, MINNESOTA

0 1 2 Miles

Existing Tailings Basin (2,900 acres total)

Area Originally Draining into Second Creek (1,000 acres)

data sources:
Historic topographic maps from U.S. Geological Survey 7.5 minute series
Embarrass, Isaac Lake, Aurora and Allen quadrangles
Published 1949 - based on 1947 air photos
Present topography (LiDAR data) from Minnesota Geospatial Information Office

February 19, 2014

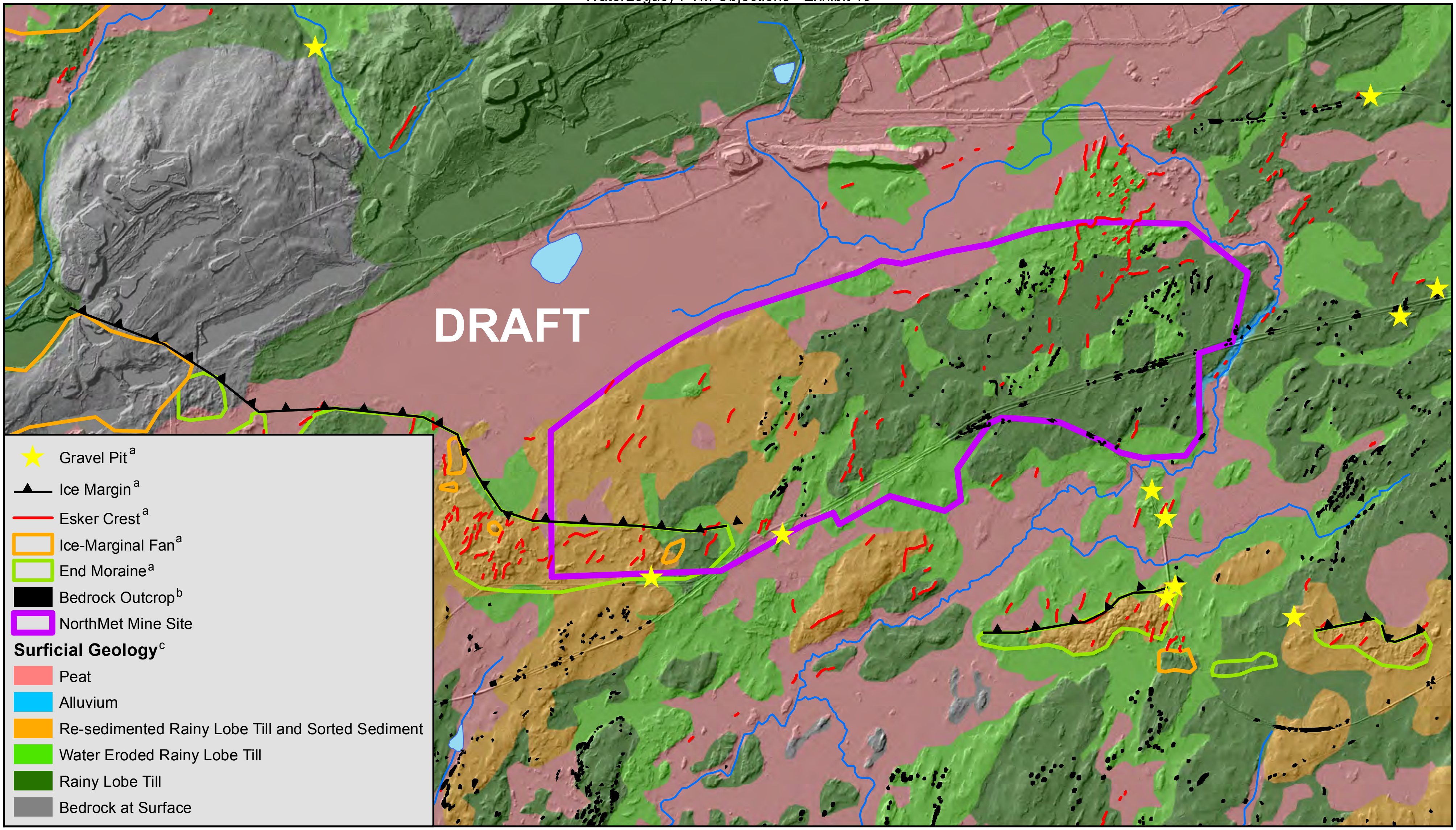


FIGURE 6

SURFICIAL GEOLOGY
VICINITY OF PROPOSED NORTHMET MINE SITE
ST. LOUIS COUNTY, MINNESOTA

Note: eskers and ice-marginal fans most often consist of sand and gravel with lesser amounts of till. End moraines most often consist of reworked till with lesser amounts of sand and gravel. Concentrations of sand and gravel are more common in close proximity to mapped ice margins.

<u>*data sources:*</u>

[a] *Lehr, J.D., 2000, The Pleistocene geology of the Embarrass area,S t. Louis County, Minnesota: Minneapolis, University of Minnesota, 157 p., map scale 1:48,000.*
Lehr, J.D., and Hobbs, H.C., 1992, Field trip guidebook for the glacial geology of the Laurentian divide area, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Guidebook Series No. 18, 73 p., map scale 1:250,000.
Unpublished mapping by J.D. Lehr 2011 to 2014

[b] *Severson, M.J., and Miller, J.D., Jr., 1999, Bedrock geology of the Allen quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-091, scale 1:24,000.*
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt quadrangle, St. Louis and Lake counties, Minnesota: Minnesota Geological Survey Miscellaneous Map Series M-159, scale 1:24,000.
Miller, J.D., Jr., and Severson, M.J., 2005, Bedrock geology of the Babbitt southwest quadrangle, St. Louis County, Minnesota: Minnesota Geological Survey Miscellaneous Map Series, M-161, scale, 1:24,000.

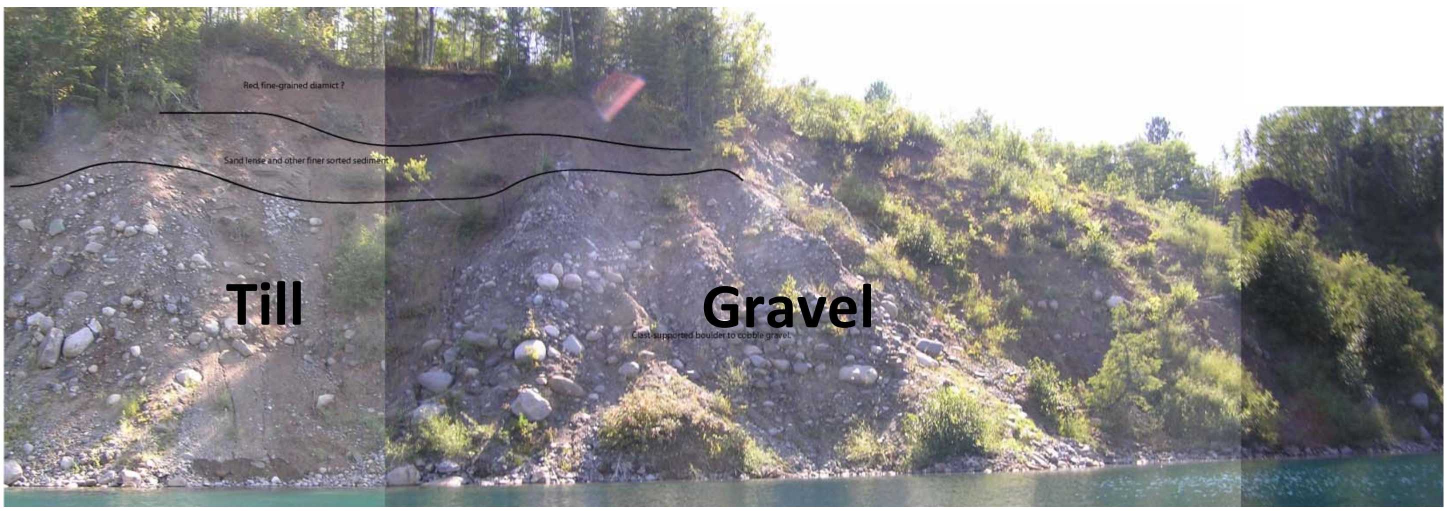
[c] *Jennings, C.E. and Reynolds, W.K., 2005, Surficial geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-164, scale 1:100,000.*
Lakes and streams from: Minnesota Department of Natural Resources
Background LiDAR image from: Minnesota Geospatial Information Office

0 — 1 Miles

February 19, 2014

Embarrass Mine

Embarrass Mine



Dunka Mine

FIGURE 7 – Photos of Potential Groundwater Conduits at Embarrass and Dunka Mines

Data source: Supplemental materials included with Jennings, C.E. and Reynolds, W.K., 2005, Surficial geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-164, scale 1:100,000.

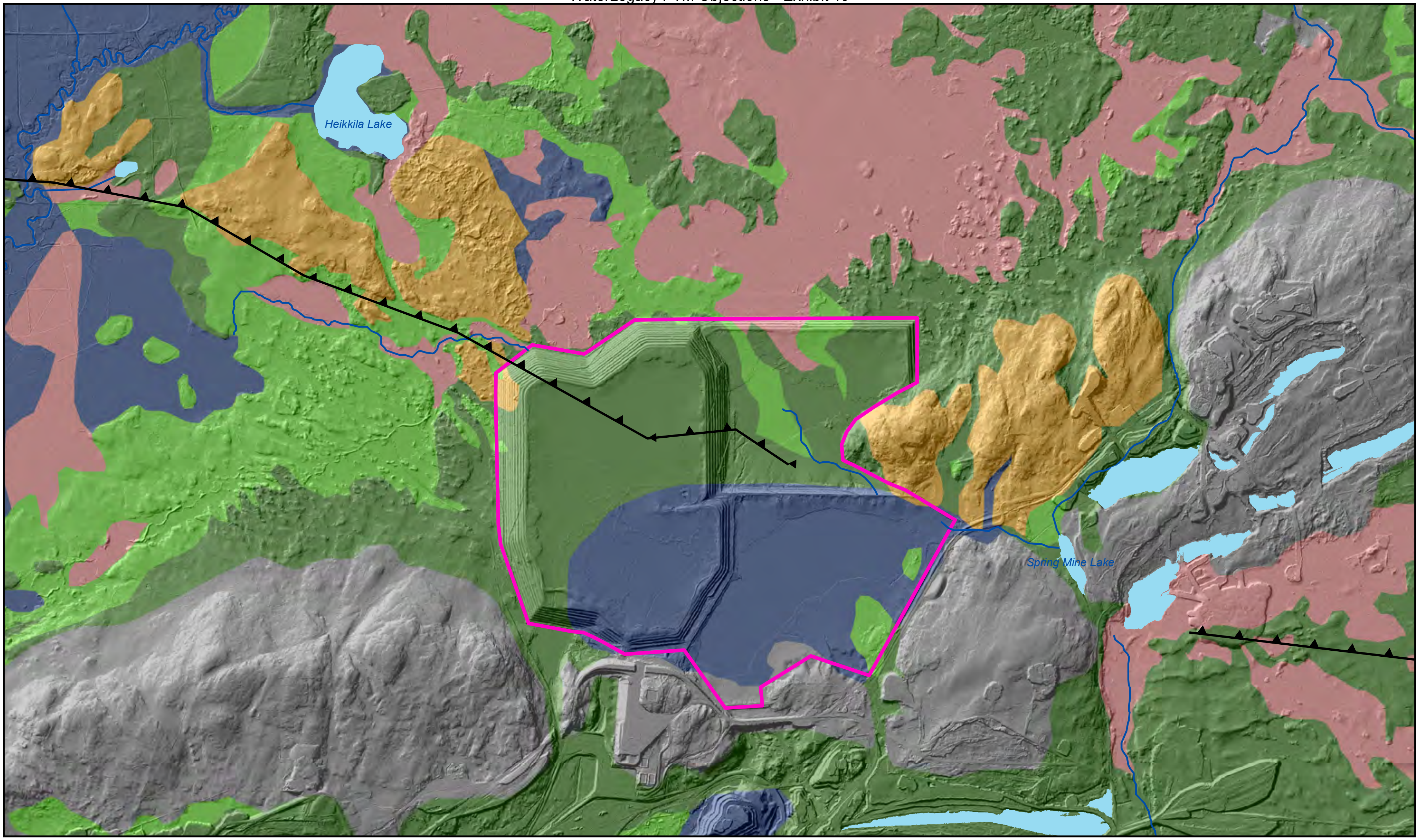


FIGURE 8

SURFICIAL GEOLOGY
VICINITY OF PROPOSED LTVSMC TAILINGS BASIN
ST. LOUIS COUNTY, MINNESOTA

<u>*data sources*</u>

Jennings, C. E., and Reynolds, W.K., 2005, Surficial geology of the Mesabi Iron Range, Minnesota: Minnesota Geological Survey Miscellaneous Map M-164, scale 1:100,000.

Streams from Minnesota DNR Data Deli. Lakes from MDNR and Minnesota Geological Survey.

Background topographic data (LiDAR) from Minnesota Geospatial Information Office

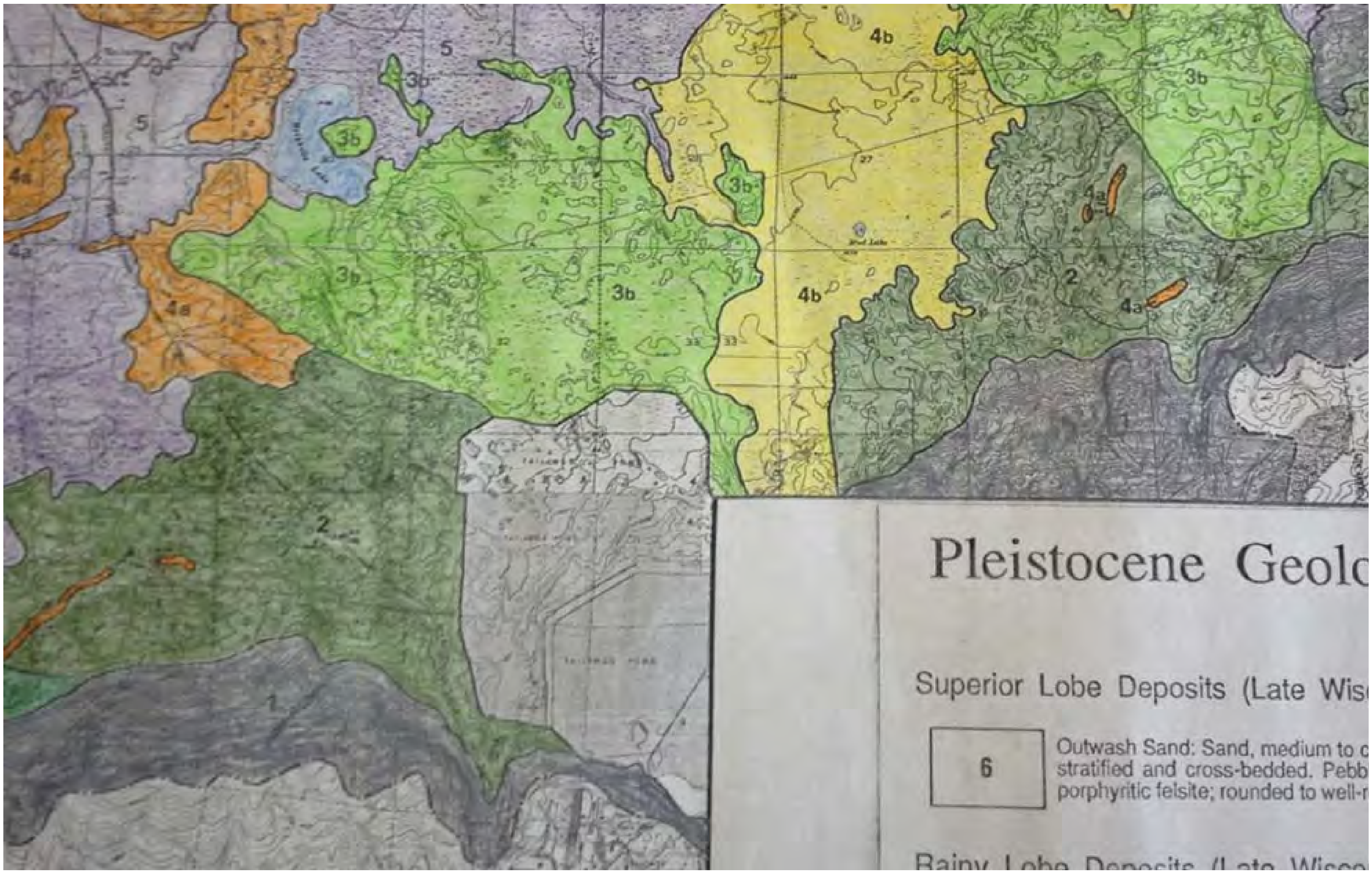
0 0.5 1 Miles

Surficial Geology (Jennings and Reynolds, 2005)

- Peat
- Lake Sediment
- Lacustrine Sediment
- Re-sedimented Rainy Lobe Till and Sorted Sediment
- Water Eroded Rainy Lobe Till
- Rainy Lobe Till
- Bedrock at Surface

- Rainy Lobe Ice Margin
- Lake
- Stream
- Existing Tailings Basin

February 19, 2014



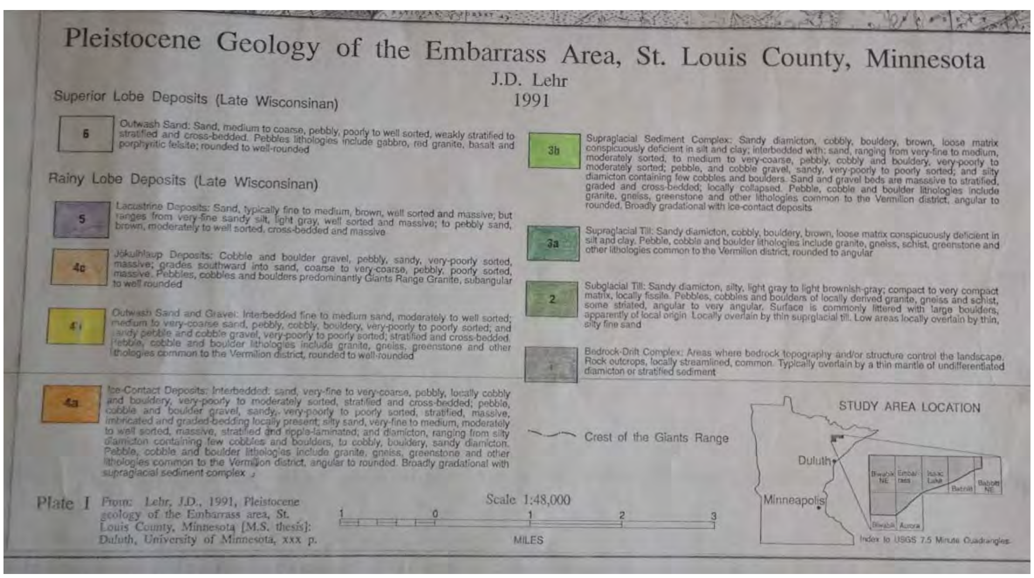


FIGURE 9 - Surficial Geology - Vicinity of LTVSMC Tailings Basin

Note: Since the publication date of the USGS quad maps used to prepare the map above (late 1960's to early 1980's) the tailings basin has expanded to the northeast into the NE1/4 section 4, the NW1/4 of section 3 and the S1/2 S1/2 section 34 into map unit 3b, a mixture of till and sand and gravel and into map unit 4b, outwash sand and gravel

Data source: Lehr, J.D., 2000, The Pleistocene geology of the Embarrass area, St. Louis County, Minnesota [M.S. Thesis]: Minneapolis, University of Minnesota, 157 p., map scale 1:48,000.

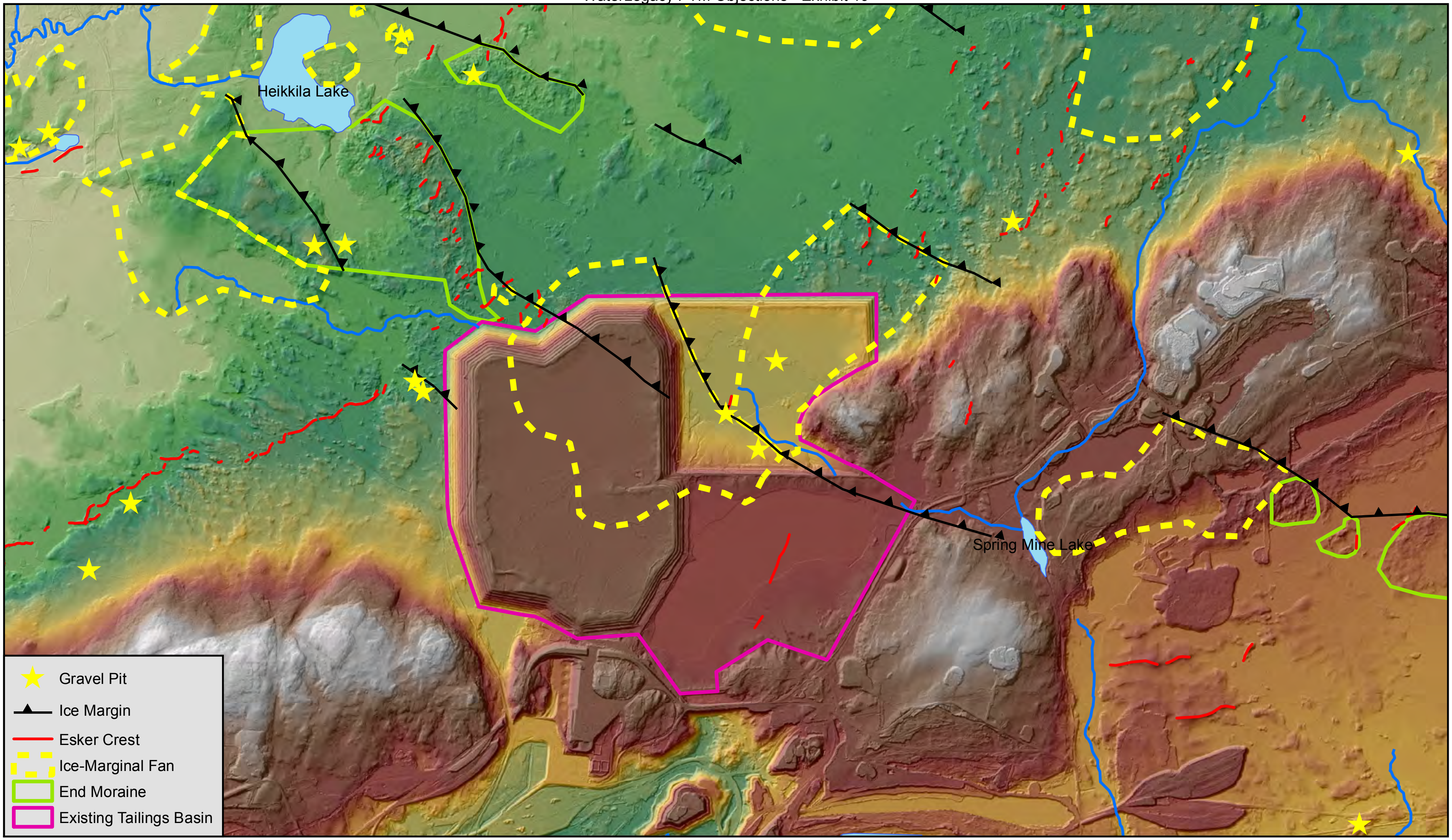


FIGURE 10

SELECTED GLACIAL LANDFORMS VICINITY OF LTVSMC TAILINGS BASIN

ST. LOUIS COUNTY, MINNESOTA

DRAFT

0 1 2 Miles

data sources:
Geology and gravel pits from:
Lehr, J.D., 2000, The Pleistocene geology of the Embarrass area, St. Louis County, Minnesota: Minneapolis, University of Minnesota, 157 p., map scale 1:48,000.
Lehr, J.D., and Hobbs, H.C., 1992, Field trip guidebook for the glacial geology of the Laurentian divide area, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Guidebook Series No. 18, 73 p., map scale 1:250,000.
Unpublished mapping by J.D. Lehr 2011 to 2014
Lakes and streams from: Minnesota Department of Natural Resources
Background LiDAR image from: Minnesota Geospatial Information Office

Note: eskers and ice-marginal fans most often consist of sand and gravel with lesser amounts of till. End moraines most often consist of reworked till with lesser amounts of sand and gravel. Concentrations of sand and gravel are more common in close proximity to mapped ice margins.

February 19, 2014

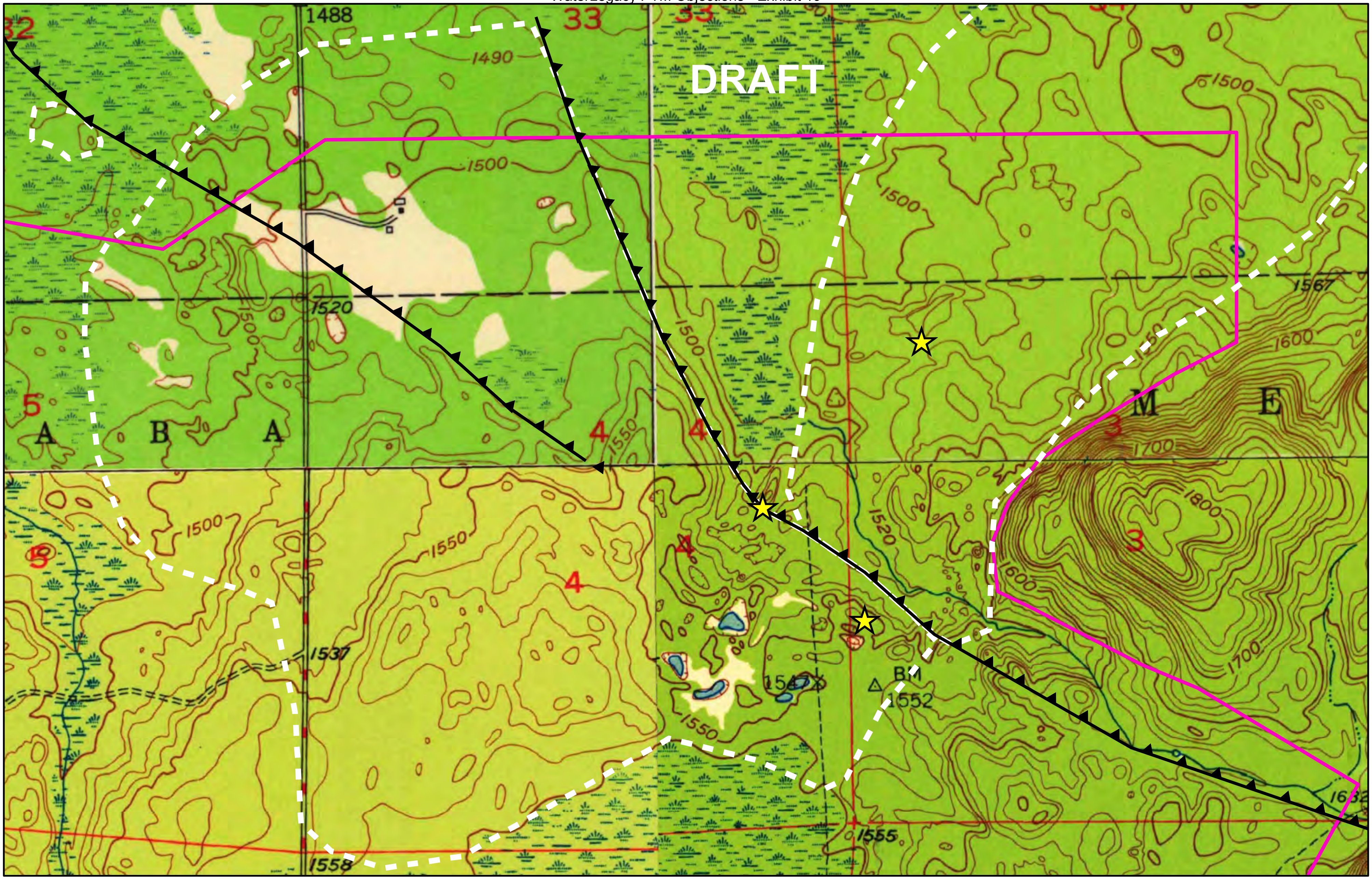


FIGURE 11

PITTED OUTWASH BENEATH LTVSMC TAILINGS BASIN VICINITY OF PROPOSED NORTHMET COPPER MINE

ST. LOUIS COUNTY, MINNESOTA

data source:
Base map from : U.S. Geological Survey 7.5 minute series Embarrass, Isaac Lake, Aurora and Allen quadrangles
Published 1949 - Based on 1947 air photos
Geology from unpublished mapping by J.D. Lehr (2014)

0 0.5 Miles

Legend

- Historic Gravel Pits
- Ice-Marginal Pitted Outwash Fan
- Existing Tailings Basin (2,900 acres total)
- Ice Margin

February 19, 2014

UNIVERSITY OF MINNESOTA

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March 13, 2014

Comment on the NorthMet Supplemental Draft Environmental Impact Statement

I recently read much of the November 2013 Supplemental Draft Environmental Impact Statement (SDEIS) entitled “NorthMet Mining Project and Land Exchange”, as well as several of the reports referenced in the document. The purpose of this commentary is to offer some suggestions that can be considered for improving the conceptual model of hydrogeologic conditions at the proposed Mine Site and Plant Site/Tailings Basin area. Improving the quality of the conceptual model will lead to improved prediction of potential impacts to groundwater, engineering of containment systems, and design of monitoring systems.

Broadly summarized, my comments focus on improving the understanding of flow through fractured bedrock. The current conceptual models in the SDEIS characterize the Duluth Complex and Giants Range Batholith bedrock as bulk masses of rock with low, uniform permeability. Although this type of characterization is sometimes deemed sufficient for some purposes, such as numerical modeling of water budgets (flux) at relatively large scales, it has well known deficiencies when applied to numerical modelling of smaller-scale sites, especially for predicting solute transport. Instead, the development of conceptual models that employ techniques whereby discrete fractures or fracture zones are more fully considered, results in improved prediction of solute transport, including better estimates of travel times, and recognition of variation in flow directions and discrete pathways in three dimensions.

Investigations aimed at characterizing the hydrogeologic conditions of fractured bedrock for the purposes of predicting solute transport in crystalline bedrock elsewhere on the Canadian Shield routinely use a number of well-known techniques that were not applied in the hydrogeologic studies at the NorthMet Mine Site and Plant Site/Tailings Basin area. A key component of those investigations is the acquisition of hydraulic and water chemistry data at relatively discrete intervals of bedrock, with the focus on fracture characterization. In part this is accomplished through testing and water sampling of boreholes constructed with relatively short open hole intervals at variable depths (e.g. “nested” wells) and/or discrete interval packer testing and water sampling of long open holes. When these techniques have been used in generally similar hydrogeologic settings elsewhere on the Canadian Shield, the results support hydrogeologic conceptual models that differ substantially from those proposed for the Duluth Complex and Giants Range Batholith described in the SDEIS. Of particular significance for solute transport, the conceptual models commonly include key fractures or fracture zones of relatively high hydraulic conductivity, and multiple flow systems within the bedrock at individual sites. These flow systems are variably connected to the surface water system, have variable residence times, can have upward and downward vertical gradients within a local area, and horizontal flow directions that differ from one another.

The data collected thus far from the proposed NorthMet Mine Site and Plant Site/Tailings Basin area are not sufficient to recognize the kinds of hydrogeologic features known to be characteristic of other crystalline bedrock settings on the Canadian Shield, described above. Nor are the data sufficient to adequately support the simpler conceptual model currently depicted in the SDEIS. The comments below specifically address where improvements could be made to the conceptual models for the Mine Site and Plant Site/Tailings basin area.

Mine site

The SDEIS indicates that hydrogeologic characterization of the mine site is based largely on single well, short-term recovery tests of 10 deep (349’-1438’) exploratory boreholes open entirely or mostly to the Duluth Complex, and multi-well, longer term aquifer tests that include 10 pumping and observation wells. The more rigorous, multi-well aquifer tests are focused on characterization of the Virginia Formation, and specifically on the potential impact of mine dewatering on nearby wetlands. Flow direction within the bedrock is based on a potentiometric map using head levels measured from bedrock holes ranging from about 50 to several hundred feet in depth. Casing is set at shallow depths in all boreholes, and therefore open-hole intervals are several tens (rare) to hundreds (common) of feet in length. Characterization of fractures at the Mine Site is based largely on inferences drawn from geologic context. For example, the SDEIS suggests that high permeability conduits for groundwater over long distances through bedrock are unlikely to apply to the Duluth Complex because its emplacement age postdates tectonic activity sufficient to generate hydrogeologically significant, extensive faults and fractures. It is also suggested that densely fractured uppermost bedrock known to be common in crystalline bedrock elsewhere in the world has been removed by glacial scouring at the Mine Site. Ultimately the conceptual model for the Duluth Complex proposed in the SDEIS is that of a “highly competent” bulk rock mass with a uniformly very low hydraulic conductivity. Numerical models based on this characterization lead to solute transport travel times exceeding one thousand years (e.g. summaries on pages 4-45 and 5-33 of SDEIS).

The SDEIS conceptual model for the Mine Site could be much better supported. First, inferences about the likelihood of extensive fractures of hydraulic significance in the Duluth complex are based on the incorrect premise of insufficient post-emplacement tectonic activity to generate such features in the region. Faults of potential hydraulic significance are common in the Duluth Complex, including near the Mine Site ((Minnesota Geological Survey (MGS) S-21 and/or MGS M-119)), and the tectonic history, as well as glacial and erosional history of the region, includes activity capable of generating extensive fracture systems that post-date emplacement of the complex. Second, the manner in which data were collected at the Mine Site, especially the use of long open hole intervals for hydraulic testing and water sampling, is insufficient to test the hypothesis that extensive high transmissivity fractures or fractured zones are absent. Discrete fractures and fractured zones commonly go unrecognized when hydrogeologic measures such as water chemistry, hydraulic conductivity, and heads are averaged across several tens to hundreds(most boreholes at the site) of feet of bedrock. Scale effect is also a factor. Boreholes are less likely to intercept hydraulically active fractures than the proposed pit walls. This also should be discussed as part of the SDEIS.

Information from outside of the Mine Site area appears to be inconsistent with the SDEIS suggestion that densely fractured uppermost bedrock has been removed by glacial scouring in the area. A site-specific example is a well-known contamination site in a younger Midcontinent Rift intrusive complex near Finland Minnesota where abundant fractures in the uppermost 100 feet of bedrock serve as fast-flow groundwater conduits (e.g. Harza Engineering Company, 1999). Furthermore, specific capacity data from Duluth Complex water wells ((County Well Index (CWI)) in northeastern Minnesota also are suggestive of enhanced fracturing in uppermost bedrock. Specific capacity tests of 366 wells in the Duluth Complex indicate hydraulic conductivities for wells open only to the upper 100 feet of bedrock are about two orders of magnitude greater than for wells open to greater depths beneath the bedrock surface. The shallower wells have average and median hydraulic conductivity values calculated from specific capacity data that are 3-4 orders of magnitude greater than the bulk conductivity value used in the modelling of the Duluth Complex at the Mine Site as described in the SDEIS.

Improved understanding of the hydrogeologic system in the Duluth Complex at the Mine site could be achieved by the acquisition of hydraulic and water chemistry data at much more discrete intervals. This would include testing and sampling of boreholes with shorter open hole intervals at variable depths (e.g. “nested” wells) and/or discrete interval packer testing and water sampling of long open holes. These techniques, along with information that can be acquired from a number of borehole geophysical tools, have been routinely applied in similar crystalline rock settings to characterize the hydrogeology of fracture systems. The hydraulic and water chemistry information from these discrete intervals in a number of boreholes would ultimately lead to an improved conceptual model for the prediction of solute transport.

Plant Site and Tailings Basin area

No subsurface hydrogeologic information was collected from the Giants Range Batholith, which underlies the Plant Site/Tailings Basin area. Instead, the hydrogeologic characterization of the Giants Range Batholith relies on a number of general observations and inferences based on geologic context. For example, the SDEIS draws on an analogy with the Mine Site, suggesting that the Giants Range Batholith is mechanically similar to the Duluth Complex, and assuming that the two units have similar stress, weathering and erosional histories, they are therefore likely to have similar hydrogeologic characteristics (SDEIS page 4-95). The conceptual model for the Giants Range Batholith is that of a single rock mass with uniformly low permeability. It is treated as a no-flow boundary.

The SDEIS would be considerably improved by providing stronger support for the conceptual model of the Giants Range Batholith described above. The use of the Duluth Complex as a hydrogeologic analogue is difficult to support. The Giants Range Batholith is Archean in age, more than 1.5 billion years older than the Duluth Complex, and therefore the assumption that the two units have similar stress, weathering, and erosional histories is not valid. As stated on page 4-45 of the SDEIS, shear zones and other hydraulically significant discontinuities are known to be common in Archean rocks of the Canadian Shield. In Minnesota, faults are known to be common across much of mapped extent of the Giants Range Batholith, including in the Plant Site/Tailings Basin area (MGS S-21 and/or MGS M-119). Hydraulically significant fractures in the Giants Range Batholith are documented to have transported contaminants at the Northwoods Closed Landfill (MPCA reports) several miles north of the Plant Site/Tailings Basin area. Furthermore, specific capacity tests of 103 water wells (CWI) in the Giants Range Batholith are indicative of the presence of enhanced fracturing in uppermost bedrock: The hydraulic conductivities calculated from specific capacity data of wells open only to the upper 100 feet of bedrock are about three orders of magnitude greater (average and median values) than for wells open to greater depths beneath the bedrock surface. The values for the shallower wells have average and median hydraulic conductivity values 3-4 orders of magnitude greater than the bulk conductivity value used for modelling of the Giants Range Batholith at the Plant Site/Tailings Basin area as described in the SDEIS.

As with the Mine Site, improved understanding of the hydrogeologic system in the Giants Range Batholith at the Plant Site/Tailings Basin area could be achieved by the acquisition of hydraulic and water chemistry data at much more discrete intervals. Hydraulic and water chemistry data from discrete intervals in shallow (<50 feet) bedrock conditions would be particularly useful to test the inference of a no-flow boundary. Bedrock groundwater chemistry could be particularly useful at this site, because constituents derived from past activities at the existing Tailings Basin may serve as a tracer to better understand solute transport through the bedrock. Such constituents have already been recognized in groundwater sampled from unconsolidated sediment in the area (SDEIS page 4-114).

SUMMARY

The SDEIS would be considerably improved with the development of conceptual models based on data derived from a number of well-established techniques that provide greater insight into fractured bedrock conditions. Improved conceptual models will lead to better prediction of solute transport, including estimates of travel times, and recognition of variable flow directions and discrete pathways in three dimensions.

Sincerely,

X 

Anthony C. Runkel
Chief Geologist
Signed by: Anthony C. Runkel

PolyMet Tailings Basin Performance

Donald W. Lee, Ph.D., P.E.

December 10, 2015

This brief report addresses the projected performance of the tailings basin for the proposed PolyMet copper nickel mine in northeast Minnesota. This note is based on the information presented in the Final Environmental Impact Statement (FEIS) for the proposed project and other supporting documentation. The comments in this note are derived from my experience in preparing and reviewing Environmental Impact Statements for controversial federal projects over 31 years of service at Oak Ridge National Laboratory. I have contributed to 16 published Environmental Impact Statements and Environmental Assessments in the areas of surface water and groundwater hydrology. I have been an expert witness in several legal proceedings regarding the conclusions presented in these documents. As these comments note, the conclusions drawn in the FEIS and the modeling performed to support these conclusions have a great deal of uncertainty. The uncertainty in the analysis is sufficient to conclude the FEIS does not provide defensible evidence of the environmental impacts to be expected from the proposed action. Given the magnitude of the PolyMet proposal, the actual impacts to water resources from the tailings basin are likely to be significant and would persist into the indefinite future.

The FEIS includes a lengthy analysis of the tailings basin, which is actually a 200 ft. tall tailings pile without a liner, for the proposed action. The FEIS concludes that 90% of the tailings leakage that remains as groundwater will be captured and contained within a containment barrier surrounding much of the tailings pile and that 100% of the surficial seepage from the tailings will be collected and contained. (FEIS 5a 179, FEIS Table 5.2.2a 37). The conclusions are based on computer models of the performance of the containment barrier and dams constructed for containing the tailings and contaminated water. The analytical support for these conclusions is based on assumptions of performance that are not justified or supported by data. Lacking any demonstration of the validity of the assumptions leaves the conclusions questionable. The resulting predictions of the effectiveness of the containment barrier in preventing the discharge of contaminants are questionable.

The tailings pile itself was originally constructed by LTV Steel Mining Company for disposing of tailings from the previous taconite mining operation. The tailings from the previous operation were placed on the ground without any liner or other form of containment. The tailings derived from taconite mining were piled to a maximum height of approximately 200 ft. at the highest point and are encircled by an earthen dam. Approximately one-half of the tailings pile has a fill depth of approximately 60 ft. from the taconite mining operations. The proposed action is to use the lower of the two filled halves of the tailings pile for the tailings from copper nickel mining. Significantly, the site of the tailings basin site included three creeks that drained to the north, east and south of the basin. While these creeks have long since been covered by a thick layer of taconite tailings, hydrologically these creeks remain functional paths for water to be discharged from the tailings basin. While the discharge of the creeks has been reduced by the thick layer of tailings placed on top of the creeks, the creeks will continue to be viable discharge locations for waters in the tailings pile in the future no matter what is done to contain the discharge.

The use of the existing tailings pile by PolyMet will increase the depth of fill within the tailings pile to 200 ft. across the entire tailings pile. Upon closure of the copper nickel mine, bentonite enriched soil will be placed on top of the tailings to allow a pond to form. This pond will cover most of the half of the tailings pile used for disposing of copper nickel tailings (FEIS Fig. 3.2-29). This pond will provide an additional 140 ft. of hydraulic head (pressure) on the base of the dam encircling the tailings pond, and will increase the leakage from the tailings pile. This phenomenon will continue for the indefinite future. Evidence of this phenomenon can be seen in the current condition of the tailings pond. FEIS Fig. 4.2.2-17 shows the existing groundwater mound associated with the tailings pile. The hydraulic gradient across the tailings pile is 150 ft. This large gradient is proportional to the flux of groundwater to the north and west of the existing tailings pile. The existing hydraulic gradient to the east suggests a limited flux, but the addition of 140 ft. of copper nickel tailings will support a notable flux of groundwater to the east as well.

FEIS Fig. 4.2.2-15 illustrates the depth to bedrock in the tailings area. The recorded depths to bedrock from drilling logs range from 3.5 – 42.5 ft. PolyMet proposes to install French drains and a slurry wall along much of the perimeter of the tailings pile (A slurry wall is a bentonite enriched soil, or bentonite and concrete enriched soil that acts to reduce the conductivity of the soil). The collected water from the French drains is to be either pumped to the Wastewater Treatment Plant or pumped back into the tailings pile. Installing a French drain and a slurry wall at a depth of over 40 ft. is a significant undertaking requiring the use of a huge shovel capable of reaching 40 ft. below the surface. More importantly, the drains are to conform to the irregular surface of the bedrock. Given the variation in the surface of the bedrock, large portions of the drainage system will require pumping to be effective as drains. The irregular surface of the bedrock and the irregular thickness of the native soils suggest a three-dimensional character of groundwater flow within the native soils. This is an important consideration, which needs to be addressed in the modeling of the site performance. This is not addressed in the analysis of the tailings pile. Failure to address the three dimensional character of the groundwater transport is certain to lead to increased leakage of contaminated groundwater from the tailings pile to the nearby surface water from the north, west, and south of the tailings pile when compared to the projected model results.

The modeling of the hydrology of the tailings facility is done using the models MODFLOW, GoldSim, and XP-SWMM. MODFLOW is used to compute groundwater movement along four different vertical cross-sections of the tailings basin. GoldSim is used to compute the transport of contaminants across several one-dimensional flow paths. XP-SWMM is used to compute surface water flow paths. Given the three-dimensional character of groundwater flow in the native soils, the reduction of the flow regime to a two-dimensional and one-dimensional domain could lead to erroneous results and questionable conclusions. There is no discussion of how the three dimensional character of the flow within the tailings pile was reduced to one or two dimensional flows. This is not an elementary exercise and could lead to results that are not representative of the site.

There is no discussion of the verification of the results from modeling, which is a standard practice in modeling. Verification of results has the purpose to demonstrate that the model(s) are indeed representative of the environment they are supposed to represent. Further guidance on this important element of modeling can be found in *Hydrology Handbook, Second Edition*, ASCE Manuals and Reports on Engineering Practice No. 28, American Society of Civil Engineers, 1996.

FEIS Table 5.2.2-12 includes the fluxes of water captured by the containment system from the tailings basin and the natural groundwater flows outside the containment system as computed by MODFLOW. Independent of concerns regarding the modeling of the tailings pile and containment system, the fluxes attributable to the containment system are significant. These results suggest the pumps for the containment system need to be sized to handle about 2517 gpm from the groundwater alone. When combined with the water management system shown in FEIS Fig. 3.2-13 and the assumption of steady state flows, the water management demands for this project are large. Given the uncertainties presented in the modeling, which is used to make these predictions, the actual performance of the water management system could be seriously mischaracterized.

FEIS Fig. 5.2.2.12 shows a flow chart for the Plant Site including the tailings pile. This figure does not include any groundwater flow from the east side of the tailings pile, which is included in the modeling of the tailings basin. This figure is not a water balance in that no quantities are included. A water balance that identifies the fluxes of water within the plant/mine sites and discharges of water from the plant/mine sites for each element of the proposed project is not presented. A comprehensive water balance accounting for water use by the proposed project would be a useful tool to verify the credibility of the modeling effort for the many aspects of the proposed project.

The leakage from the pond on the top of the tailings basin is specified to be 6.5 in/yr. The text points out "The 6.5 in/yr pond leakage rate is not computed, but is a stated engineering performance specification. The hydraulic conductivity that achieves this leakage is computed using a credible Darcy's Law calculation" (FEIS A-579). Darcy's Law is a simple formula that states the flux of water through a porous media is equal to the product of the hydraulic conductivity and the hydraulic gradient. In effect, this statement assumes a solution without providing any justification for the assumption. Freezing and thawing are certain to degrade the liner with a certain increase in leakage. The long-term performance of this pond on top of the tailings pile is assumed to be constant for the indefinite future. This assumption is not justified and would be nearly impossible to justify for the long term. Since evaporation is less than precipitation in Minnesota, increased infiltration can be anticipated, which will lead to increased discharge of contaminated water from the tailings pile to surface water for the indefinite future.

The analysis of the surficial deposits or native soils presumes the hydraulic characteristics are single-valued in the MODFLOW modeling for both the horizontal and vertical directions. The modeling does not include any accounting for groundwater flow in the unsaturated zone or accounting for variations in hydraulic conductivity in the horizontal or vertical directions.

Considering soil properties to be homogeneous over large areas and depths is a significant assumption that is not justified or addressed. Failure to address these considerations leaves the modeling open to question. Data supporting the single value hydraulic characteristics are not presented. The supporting documentation is where these data are to be found. The referenced data for the tailings pile include the hydraulic conductivity range from 3.4E-4 ft/day to 2 ft/day ("Hydrogeology of Fractured Bedrock in the vicinity of the NorthMet Project" Barr, 2014b). How a single value can be assigned to this range of data is not justified. Lacking a justification for the selection of a single value leads to predictions that are uncertain, which leads to conclusions that are indefensible.

An important feature of the tailings basin containment system is the slurry wall. The slurry wall (referred to in the FEIS as a cutoff wall) is supposed to be keyed into bedrock in some descriptions (FEIS Fig. 5.2.2-14) and not in others (FEIS Fig. 3.2-28). The FEIS suggests the slurry wall is to be nearly impermeable for the indefinite future without any justification. The descriptions of the bedrock suggest that the upper portions of bedrock have greater conductivity, while the deeper portions are less conductive. However, the MODFLOW calculations were done with the bedrock being described as a no-flow barrier. Quoting the text, "It is acknowledged that the Plant Site MODFLOW model does not include bedrock. This is because the bulk hydraulic conductivity of the upper bedrock is estimated to be about two orders of magnitude lower than the hydraulic conductivity of the surficial aquifer, and it is interpreted that deeper bedrock has substantially lower hydraulic conductivity." However, FEIS Fig. 5.2.2-14 and FEIS Fig. 5.2.2-15 illustrate groundwater flow beneath the slurry wall. The FEIS leaves unresolved how a slurry wall is to be installed in bedrock and how effective it can be. Also remaining is the question of how much groundwater is actually flowing in bedrock rather than relying on estimates or interpretations not based on data.

The role of bedrock in the groundwater flow in and around the tailings basin is not viewed with any consistency in the FEIS or the supporting documentation. The data presented in the Barr (2014b) report includes the existence of an artesian well that produces 10-12 gpm. Artesian wells are not typically associated with an unconfined surficial aquifer, especially with a discharge of 10-12 gpm, but are usually associated with a confined aquifer overlain by clay or a tight rock formation. Other than appearing in the data included in the Barr (2014b) report, no explanation is provided. The lack of consistency within the analysis yields inconsistent conclusions.

The FEIS analysis of the tailings pile is questionable for the reasons listed above and for the many inconsistencies within the analysis. The supporting data contained in PolyMet technical reports and not in the FEIS are subjected to arbitrary interpretations prior to use in modeling. The representativeness of PolyMet's modeling results with the actual performance of the tailings basin is open to argument. Absent from the analysis is the long-term performance of the tailings pile. While the conclusions of the FEIS are not supported, the conclusions confirm that the tailings pile likely will remain an environmental concern for the indefinite future. This is disconcerting for the groundwater and surface water resources of the St Louis River watershed.

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Senior Research Scientist, Energy Division (2000 – 2001), Environmental Sciences Division (2001 – 2008). Research in waste management and safety analysis, preparation of Environmental Impact Statements for energy related projects.

1997 – 2000 OAK RIDGE NATIONAL LABORATORY

Program Manager, Waste Management and Safety Analysis Program, Center for Energy and Environmental Analysis, Energy Division. Manager of Division work in radioactive, hazardous, industrial, and mixed waste management and safety analysis. Major activities include performance assessment and safety analysis reports for DOE sites.

1989 – 1997 OAK RIDGE NATIONAL LABORATORY

Research and Development Group Leader, Applied Physical Sciences Group, Environmental Analysis and Assessment Section, Energy Division. Manager of Section work in radioactive waste management and safety analysis. Focus of research was on geologic and hydrologic analysis. Preparation of performance assessments fpr DOE low-level radioactive waste disposal facilities. Conduct of site-specific analyses for waste management, Safety Analysis Reports, Environmental Restoration, and Environmental Impact Statements. Manager of a staff of 7 with a budget of $2 million.

1982 – 1989	OAK RIDGE NATIONAL LABORATORY
	Research Staff, Energy Division. Preparation of technical analyses of water resource issues in radioactive waste management, in-situ uranium mining, uranium milling, synfuels technologies, and hydropower. Development of waste management strategies for Lockheed Martin facilities, performance of site characterization studies of low-level radioactive waste disposal sites. Preparation of Environmental Impact Statements and Environmental Assessments for energy related projects.
1977 – 1982	OAK RIDGE NATIONAL LABORATORY
	Research Associate, Energy Division. Preparation of Environmental Impact Statements, Environmental Assessments, and environmental analyses of nuclear, coal, geothermal, and conservation technologies. Conduct research investigations in environmental monitoring, surface water hydrology, and groundwater hydrology using theoretical, numerical, and field methods.
1971 – 1976	UNIVERSITY OF MICHIGAN
	Research/Teaching Assistant. Performance of laboratory research in the field of tire mechanics, Instructor for rigid body dynamics, statics, strength of materials, and advanced numerical analysis.
1975 – 1976	WAYNE STATE UNIVERISTY
	Instructor in physics, energy, energy policy, values, and microbiology.
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1969 – 1970	FORD MOTOR COMPANY
	Product Design Engineer, Engine and Foundry Division, Research and Development Center.

Education

1977	Ph. D., Applied Mechanics, University of Michigan, Ann Arbor, Michigan.
1973	M. S., Engineering Science, Clarkson College of Technology, Potsdam, New York.
1969	B. S., Mechanical Engineering, Clarkson College of Technology, Potsdam, New York.

Professional/Academic Honors

Pi Tau Sigma, Mechanical Engineering Honor Fraternity, 1969
Registered Professional Engineer,
State of Michigan, 1977
State of Tennessee, 1978
Significant Event Award, Martin Marietta Energy Systems, 1991
Significant Event Award, Lockheed Martin Energy Systems, 1995
Board Certified, American Academy of Environmental Engineers, 1996 – 2007
In Appreciation, American Society of Civil Engineers, Environmental Engineering Division, 1992
In Appreciation, American Society of Civil Engineers, Environmental Engineering Division, 1999
Certificate of Appreciation, Defense Logistics Agency, Department of Defense, 2005
Who's Who in Science and Engineering, 2007
Who's Who in America, 2007
Who's Who in the World, 2007
Retirement Certificate, Oak Ridge National Laboratory, 2008

Professional Activities

Reviewer, American Society of Civil Engineers, Hydraulics Division (1982 – 1996)
Reviewer, Elsevier Publishing Co. (1987)
Reviewer, Nuclear and Chemical Waste Management (1986 – 1995)
Member, American Society of Civil Engineers
Member, American Society of Mechanical Engineers
Member, Sigma Xi
Member, DOE Waste Classification Working Group, 1987
Member, DOE Task Force on Uranium Waste Problems, 1988
Member, DOE Low-Level Radioactive Waste Technical Resource Group for 40 CFR 193, 1988
Member, DOE Low-Level Radioactive Waste Peer Review Committee for DOE Order 5820.2A, 1988 – 1997
Member, DOE Performance Assessment Technical Resource Group for DOE Order 5820.2B, 1994 – 1995
Member, DOE Federal Facilities Compliance Act Disposal Work Group, 1994 – 1996
Member, DOE Defense Nuclear Facilities Safety Board Recommendation 94-2, Site Assessment Team, 1995
Member, DOE Defense Nuclear Facilities Safety Board Recommendation 94-2, Research and Development Task Team, 1995
Member, DOE Defense Nuclear Facilities Safety Board Recommendation 94-2. Working Group Assessment Team, 1995
Member, DOE Order 435.1 Revision Team, 1996 – 2000
Adjunct Associate Professor, North Carolina State University, Department of Mechanical and Aerospace Engineering, 1987 – 2000

Ph. D. Dissertation Committee Co-Chairman, North Carolina State University, Department of Mechanical and Aerospace Engineering, 1987 – 1993

Secretary, Air and Radiation Management Committee, Environmental Engineering Division, American Society of Civil Engineers, 1989 – 1990

Vice-Chairman, Air and Radiation Management Committee, Environmental Engineering Division, American Society of Civil Engineers, 1990 – 1981

Chairman, Air and Radiation Management Committee, Environmental Engineering Division, American Society of Civil Engineers, 1991 – 1992

Secretary, Programs Committee, Environmental Engineering Division, American Society of Civil Engineers, 1992 – 1994

Member, American Society of Civil Engineers Task Committee on Mixed Waste, 1988 – 1993

Vice-Chair, Professional Activities Committee, Environmental Engineering Division, American Society of Civil Engineers, 1994 – 1996

Chair, Professional Activities Committee, Environmental Engineering Division, American Society of Civil Engineers, 1996 – 1999

Secretary, Conference and Exhibits Council, Environmental and Water Resources Institute, American Society of Civil Engineers, 2001 – 2003

Member, Conference and Exhibits Council, Environmental and Water Resources Council, American Society of Civil Engineers, 1999 – 2001, 2003 – 2005

Session Moderator, Radiation Management, National Conference on Environmental Engineering, Reno, Nevada, 1991

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National Abstract Review Committee, 1991 National Conference on Environmental Engineering, American Society of Civil Engineers

Reviewer, Journal of Environmental Engineering, American Society of Civil Engineers, 1995 – 2005

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National Abstract Review Committee, 1999 National Conference on Environmental Engineering, American Society of Civil Engineers

Technical Organizing Committee, 2000 National Conference on Environmental Engineering, American Society of Civil Engineers

Organizing Committee, International Water Congress 2001, American Society of Civil Engineers

Conference Chairman, 2002 Joint CSCE/ASCE International Conference on Environmental Engineering, Niagara Falls, Ontario

Session Moderator, Risk, 2002 Joint CSCE/ASCE International Conference on Environmental Engineering, Niagara Falls, Ontario

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Technical Memorandum

To: Poly Met Mining Inc. (PolyMet)
From: Tom Radue and Christie Kearney
Subject: Groundwater Containment System: Degree of Use in Industry
Date: December 26, 2012
Project: 23/69-0862

A groundwater containment system will be constructed around the Category 1 Waste Rock Stockpile to collect stockpile drainage in lieu of a liner system under the stockpile. This memorandum was developed to document the degree to which groundwater containment systems are used in industry today.

Containment systems such as the Category 1 Stockpile Groundwater Containment System are commonly used at facilities where there is a need to manage groundwater flow, such as landfills, tailings basins, and paper sludge disposal facilities. The combined use of a cutoff wall and a groundwater collection system is acknowledged by academic, governmental and industry authorities, and by construction markets (i.e., MoreTrench [http://www.moretrench.com], Hayward Baker [http://haywardbaker.com] and other cutoff wall construction contractors). By way of example, the United States Department of Labor's Mine Safety and Health Administration has developed design guidance for coal refuse facilities that illustrates various designs for the construction of cutoff wall and groundwater collection systems for the purposes of impoundment stability and water quality management (Reference (1)).

The United States Army Corp of Engineers (Reference (2)) and Department of the Interior's Bureau of Reclamation (Reference (3), Reference (4)) have developed design guidance for dams that illustrates various designs for the construction of cutoff wall and groundwater collection systems for the purposes of impoundment stability and water discharge management. These design guidance documents provide the supporting theory, field data requirements, construction recommendations, and typical post-construction performance monitoring procedures for the installation of cutoff wall and groundwater collection systems.

Large Table 1 provides a list of 15 sites, identified by a data search, having containment systems such as that planned for the Category 1 Waste Rock Stockpile. One such example is the constructed cutoff wall and collection system for water quality management in Taunton, Massachusetts. To control and collect groundwater contamination associated with a former pharmaceutical manufacturing facility, a cutoff wall and groundwater collection trench with perforated drain pipe were installed. The cutoff wall (approximately 50-feet deep and 3-feet wide) was constructed next to the 12-foot wide collection trench. The collection trench was equipped with a 4-inch schedule 40 PVC perforated pipe, wrapped in geotextile and bedded with crushed stone. Another example is the installation of a soil-bentonite cutoff wall around the perimeter of a mine tailings pond located in the province of Alberta, Canada. The cutoff wall is approximately 100-feet deep and 3 feet wide, and has a hydraulic conductivity of less than $1x10^{-7}$ cm/sec. The cutoff wall was used to isolate the tailings pond from downgradient surface water features including wetlands and the Athabasca River. Other such examples are shown on Large Table 1 with references listed for further review of each example.

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Large Table 1 Examples of Containment Systems at Other Sites

Location	Reference	Project Setting	Barrier Wall	Trench Dimensions	Seepage Collection	Seepage Collection Pipe	Cover
Carlsbad, NM	(5)	Potash Process Disposal	Slurry wall	10 feet deep	Yes	Yes	None
Duncan, OK	(6)	Landfill Remediation	80 mil HDPE panels	35 feet deep	Yes	No	Native soil
Tacoma, WA	(6)	Wood Process Waste Landfill	Bentonite	30 feet deep	Yes	No	GCL
Dallas, TX	(6)	Landfill Remediation	2x40 mil HDPE panels	35 feet deep	Yes	6-inch PVC	None
Bogalusa, LA	(7)	Papermill Landfill	Soil-bentonite	40 feet deep, 2.5 feet wide	Yes	Yes	None
Oak Ridge, TN	(8)	DOE Landfill	Soil-bentonite	22 feet deep	Yes	No	None
San Antonio, TX	(8)	USAF Landfill	Slurry	40 feet deep, 3 feet wide	Permeable Reactive Barrier (PRB)	No	None
Taunton, MA	(6)	Pharmaceutical Mfr Remediation	Bentonite	55 feet deep, 12 feet wide	Yes	4-inch PVC	Multi-composite liner
Toledo, OH	(6)	MGP Mfr Remediation	Bentonite	Yes, dimensions not listed	Yes	No	Native soil
Salt Lake City, UT	(7)	Watkins Dam Restoration	Cement-bentonite	70 feet deep, 2.5 feet wide	18 feet deep, 3 feet wide	No	None
Burbank, CA	(6)	Brownfield Remediation	Soil-bentonite	60 feet deep	No	No	None
Coahoma, TX	(6)	Oil Field Remediation	None	12 feet deep, 3 feet wide	Yes	No	HDPE
Beaumont, TX	(6)	Creosoting Facility Remediation	Soil-bentonite	50 feet deep	Yes	No	None
Greely, CO	(7)	Former Gravel Quarry	Soil-cement-bentonite	65 feet deep, 3 feet wide	No	No	None
Fort McMurray, Alberta, Canada	(7)	Mine Tailings Pond	Soil-bentonite	100 feet deep, 3 feet wide	No	No	None

CANADA

Federal study says oil sands toxins are leaching into groundwater, Athabasca River

BOB WEBER
EDMONTON
FROM FRIDAY'S GLOBE AND MAIL
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New federal research has strongly backed suspicions that toxic chemicals from Alberta's vast oil sands tailings ponds are leaching into groundwater and seeping into the Athabasca River.

Leakage from oil sands tailings ponds, which now cover 176 square kilometres, has long been an issue. Industry has acknowledged that seepage can occur, and previous studies using models have estimated it at 6.5-million litres a day from a single pond.

The soil around the developments contains many chemicals from naturally occurring bitumen deposits, and scientists have never able to separate them from contaminants released by industry.

The current Environment Canada study, accepted for publication in the journal Environmental Science and Technology, used new technology to discover that the mix of chemicals is slightly different between the two sources. That discovery, made using a $1.6-million piece of equipment purchased in 2010 to help answer such questions, allows scientists to actually fingerprint chemicals and trace them back to where they came from.

"Differentiation of natural from [tailings water] sources was apparent," says the study.

The scientists took 20 groundwater samples from areas at least one kilometre upstream and downstream from development. They took another seven samples from within 200 metres of two of the tailings ponds. Samples were also taken from two different tailings ponds.

The analysis was focused on so-called acid-extractable organics, which include a family of chemicals called naphthenic acids. "Their enhanced water solubility makes them prime candidates for possible migration beyond containment structures via groundwater," the report ys.

water from the ponds.

"Analyses all demonstrate a close similarity between these two [near] samples and [tailings water], as opposed to the natural far-field groundwater," the report says.

"The resemblance between the [acid-extracted organics] profiles from [tailings water] and from six groundwater samples adjacent to two tailings ponds implies a common source. These samples included two of upward-flowing groundwater collected [less than] one metre beneath the Athabasca River, suggesting [tailings water] is reaching the river system."

The study doesn't quantify the amount of tailings ponds water that is escaping.

It noted that even at the sample sites near development, pond water was diluted by natural groundwater.

The research was conducted under the auspices of the Joint Oilsands Monitoring Program run by the federal and Alberta governments and funded by a $50-million levy on industry.

Industry is working to address the tailings issue, budgeting more than $1-billion in tailings-reduction technology.

Groundwater is monitored at all tailings sites to ensure it's flowing as expected. Operators use ditches and cut-off walls to capture seepage and runoff water, and install groundwater interception wells. Captured water is pumped back into tailings ponds.

Mark Cooper, spokesman for the Canadian Association of Petroleum Producers, said the quality of water in the Athabasca River remains good.

"Current tailings pond and groundwater monitoring in the oilsands shows no substances being released or predicted to be released in quantities or concentrations that would degrade or alter water quality," he said. "This study does not change that."

Mr. Cooper said the association supports research such as the Environment Canada study and echoed its call for more research in the same vein. "While the research technique used in this study shows some potential, further detailed work is required to evaluate its accuracy and adequacy for tracking oil sands process water."

WaterLegacy PTM Objections
Exhibit 24

Environmental Science & Technology

Article

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Profiling Oil Sands Mixtures from Industrial Developments and Natural Groundwaters for Source Identification

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Supporting Information

ABSTRACT: The objective of this study was to identify chemical components that could distinguish chemical mixtures in oil sands process-affected water (OSPW) that had potentially migrated to groundwater in the oil sands development area of northern Alberta, Canada. In the first part of the study, OSPW samples from two different tailings ponds and a broad range of natural groundwater samples were assessed with historically employed techniques as Level-1 analyses, including geochemistry, total concentrations of naphthenic acids (NAs) and synchronous fluorescence spectroscopy (SFS). While these analyses did not allow for reliable source differentiation, they did identify samples containing significant concentrations of oil sands acid-extractable organics (AEOs). In applying Level-2 profiling analyses using electrospray ionization high resolution mass spectrometry (ESI-HRMS) and comprehensive multidimensional gas chromatography time-of-flight mass spectrometry (GC × GC-TOF/MS) to samples containing appreciable AEO concentrations, differentiation of natural from OSPW sources was apparent through measurements of O_2:O_4 ion class ratios (ESI-HRMS) and diagnostic ions for two families of suspected monoaromatic acids (GC × GC-TOF/MS). The resemblance between the AEO profiles from OSPW and from 6 groundwater samples adjacent to two tailings ponds implies a common source, supporting the use of these complimentary analyses for source identification. These samples included two of upward flowing groundwater collected <1 m beneath the Athabasca River, suggesting OSPW-affected groundwater is reaching the river system.

1. INTRODUCTION

The Canadian oil sands region contains an estimated 168.6 billion barrels of recoverable bitumen,[1] accounting for 97% of Canada's petroleum reserves and ranking Canada third globally in terms of domestic oil reserves.[2] Recent studies investigating the loading of inorganic and neutral organic compounds have identified significant aerial depositions of priority pollutants[3,4] associated with mining activities. These results, combined with recent calls for a greater understanding of the potential environmental impacts resulting from industrial development of the oil sands,[5−7] have catalyzed the implementation of a new Canada−Alberta Joint Oil Sands Monitoring Program (JOSMP[8]).

One of the objectives of the JOSMP is to evaluate the nature and extent of the possible migration of contaminants associated with mining developments to regional aquatic ecosystems.[5,7] The proximity of several large containment structures (e.g., tailings ponds) containing oil sands process-affected water (OSPW) to the Athabasca River and its tributaries provides an obvious focus for this investigation. Process-affected waters contain complex mixtures of neutral and polar organic compounds, in addition to dissolved metals and major ions (e.g. Na, Cl, SO_4, HCO_3).[9] Of significance are the acid-extractable organics (AEOs), which include naphthenic acids (NAs). These are attractive from a monitoring perspective because they have demonstrated acute[10,11] and sublethal[12] toxicity.[13] Furthermore, their enhanced water solubility makes them prime candidates for possible migration beyond containment structures via groundwater, which is important given the zero-discharge policy for surface water releases within mining lease licenses. Advancements in analytical techniques including electrospray ionization high resolution mass spectrometry (ESI-HRMS) and comprehensive multidimensional

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gas chromatography time-of-flight mass spectrometry (GC × GC-TOF/MS) have shown that mixtures of oil sands-derived AEOs include compounds containing aromatic rings,[14−16] other multiple oxygenated acid species, and sulfur- and nitrogen-heteroatoms.[17−22]

Several studies have shown or suggested leakage of OSPW into groundwater and migration of OSPW-affected groundwater away from impoundments.[23−27] Numerical modeling[23,24] estimated leakage from the base of one impoundment and dyke at <75 L s^{-1} (about 0.1% of the lowest daily Athabasca River flow recorded, 75 m^3 s^{-1}).[28] A plume of OSPW-impacted groundwater has also been mapped to extend approximately 500 m away from another nearby impoundment.[25,26] In these studies, a variety of geochemical and organic signatures have been employed[24,26,29] in attempts to track potential leakage, including: bicarbonate,[24,30] sodium,[30] the sodium to chloride ratio, the water type as indicated by its position on a Piper plot, boron, ammonium,[25,26] and various measures of AEOs (including by Fourier transform infrared spectroscopy (FTIR), ESI-MS, synchronous fluorescence spectroscopy (SFS[16,31])). Although advanced analytical and chromatographic techniques such as ESI-HRMS,[19,32] APPI-HRMS[33,34] and GC × GC-TOF/MS[31,35−37] have provided breakthroughs in the identification of classes within OSPW-derived AEO mixtures, there has been minimal progress differentiating the similar, but less-studied, AEO mixtures present in the natural background waters within the McMurray Formation.[19] Given the large areas requiring monitoring under the JOSMP, it is important to establish whether a unique chemical profile of OSPW exists that could be employed to identify and track OSPW-affected groundwater and surface waters.

Recent attempts to profile industrial and natural waters from the oil sands region have begun to indicate potential chemical markers for successful differentiation. For example, a 2011 pilot study[38] at one tailings impoundment used ESI-HRMS and ^{13}C isotopic signatures of the carboxylic acid functional groups in NAs for profiling. This study, and a related study[39] that compared ^{13}C isotopic signatures between OSPW, monitoring wells, unprocessed oil sand and Athabasca River water, illustrates the potential of these techniques for differentiation. To date, the most complete study used liquid-chromatography (LC)-ESI-TOF/MS to profile oil sands AEOs in lakes, the Athabasca River and some of its tributaries, and pore water (e.g., potentially discharging groundwater) collected from the Athabasca River.[27] Although this investigation indicated that similarities in surface water compositions of two tributaries and OSPW were suggestive of seepage, the clustering of OSPW and pore water sites following principal components analysis made differentiation difficult. Consequently, the application of more specific analytical techniques was recommended. Furthermore, it is important to note that a systematic investigation, beyond proof-of-concept, examining the range of naturally occurring bitumen-derived AEO, lacking any possible OSPW influence, has yet to be conducted.

The objective of the present study was to identify chemical components that could distinguish OSPW-affected groundwater from natural groundwater containing bitumen-derived AEOs within the McMurray Formation. The first part of the study involved application of Level-1 analyses consisting of assessing geochemistry (major ions, Na, B, NH_4), total AEO concentrations, and the presence/absence of maxima in a SFS profile characteristic of oil sands mono- and diaromatic NAs, to two different OSPW containments and a broad variety of natural groundwater samples. Level-2 analyses, consisting of advanced separation and ESI-HRMS techniques, were then applied to differentiate bitumen-derived AEO mixtures originating from OSPW from those naturally present in groundwater in the oil sands region. In the second part of the study, both Level-1 and 2 analyses were applied to groundwater samples collected adjacent to two tailings ponds to determine whether their chemical profiles resembled those of natural or OSPW sources.

2. MATERIALS AND METHODS

2.1. Sample Collection. For the first part of the study, duplicate samples of OSPW were collected from each of two tailings ponds from different oil sands developments between September 20 and 25, 2009 (OSPW 1, 2; Figure 1). Far-field groundwater samples (15−20 mL) were collected from 20 sites. One groundwater seep sample collected in the Joslyn Creek catchment was obtained on October 19, 2010, directly from groundwater discharging to the surface at the seepage face. The remaining 19 were collected using a stainless steel drive-point system[40] at depths of 30−120 cm below the streambed of the Athabasca River and associated tributaries (Ells River, Steepbank River) between May and October 2010. Far-field was defined in this study as >1 km upstream or downstream from any tailings pond, given the likely dominance of groundwater flow perpendicular to the Athabasca River. Level-1 analyses of these samples included the assessment of geochemical parameters (defined below), total AEO concentrations (referred to in the Results as [NA] and determined by low resolution ESI-MS), and expected maxima in an SFS profile associated with suspected mono- and diaromatic acids.[31] Far-field samples containing appreciable amounts of NAs (>5 mg L^{-1}) and both OSPW samples were selected for detailed profiling by ESI-HRMS and GC × GC-TOF/MS. For the second part of this investigation, a total of seven near-field samples (<200 m from an OSPW containment) were collected near two tailings ponds. Two samples were collected from Site A: an interceptor well and a monitoring well. In addition, five samples were collected from Site B: an interceptor well, a monitoring well, and three drive-point groundwater samples along the western shore of the Athabasca River. On-development interceptor and monitoring wells (4.8−39.0 m depths) were sampled June 22−23, 2010, while drive point samples were collected as noted above. All near-field samples underwent Level-2 analyses for comparison with OSPW and far-field samples with appreciable NAs, in addition to Level-1 analyses. Locations of the near- and far-field samples selected for AEO profiling are presented in Figure 1.

2.2. Geochemical Analysis. Measured geochemical parameters comprised anions (including chloride, sulfate, and nitrate) analyzed by ion chromatography, major cations (including sodium and calcium) analyzed by direct aspiration using an inductively coupled argon plasma system,[40] and ammonium analyzed by spectrophotometry using a phenolhypochlorite reagent (absorbance measured at 640 nm). Samples were also analyzed for a suite of trace metals (including boron) at Environment Canada's National Laboratory for Environmental Testing (NLET) (Burlington, ON) using Inductively Coupled Plasma-Sector Field Mass Spectrometry.[41] Samples were categorized into different water types according to the relative balances of major ions as depicted on a Piper plot, which is a graphical technique commonly applied in groundwater studies.[24,27]

2.3. Synchronous Fluorescence Spectroscopy (SFS). Analysis by SFS was performed using a Perkin-Elmer Luminescence spectrometer LS50B and data collection was controlled

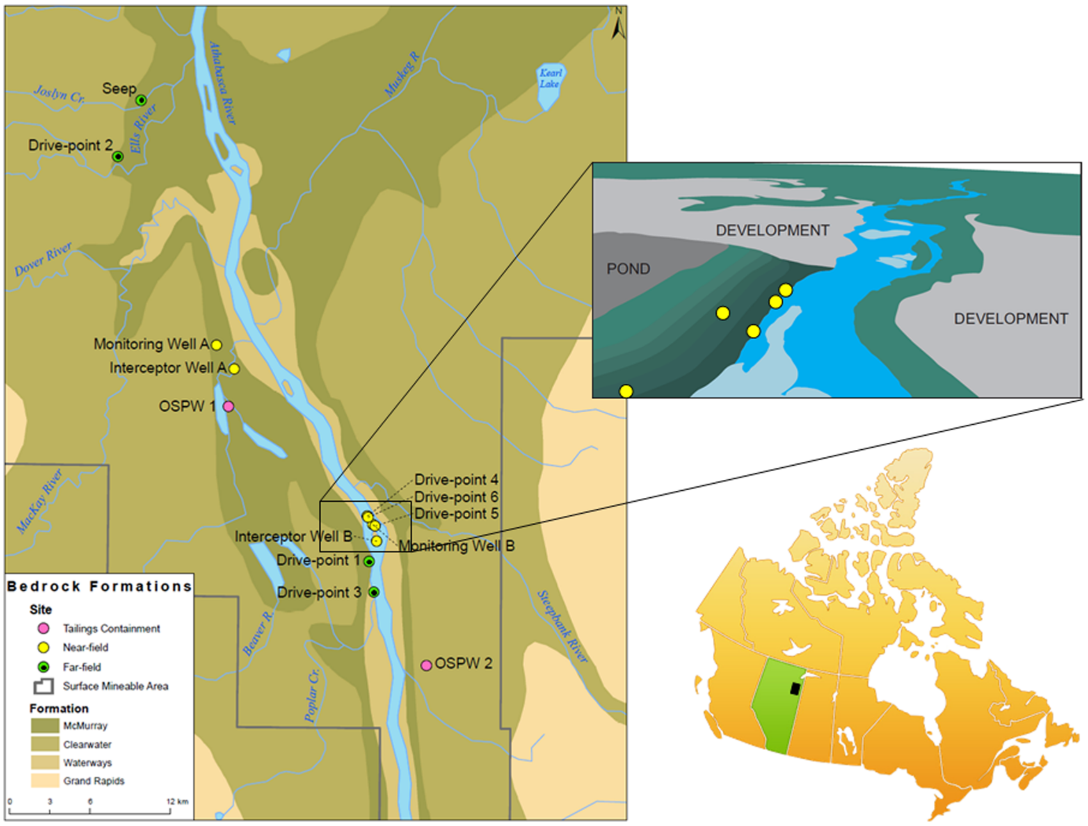

Figure 1. Map depicting sampling locations of OSPW, Near-field and Far-field locations prioritized for Level-2 profiling. Inset depicts close-up of area illustrating locations of Site B Near-field drive-points, interceptor and monitoring wells.

by FL Winlab 3 software (Perkin-Elmer, Norwalk, CT) as previously described.[16] The expected maxima for an SFS oil sands NA profile are at 282, 320, and 333 nm.[16,31] In this investigation, samples that exhibited maxima at 282 and 320 nm above a signal intensity of 100 were identified as positive for this profile.

2.4. Sample Preparation for Detailed Profiling. Prior to analysis by ESI-HRMS and GC × GC-TOF/MS, all samples were extracted by solid phase extraction (SPE) to remove residual salts and to concentrate polar organics. For each 15-mL sample, a 200 mg styrene divinylbenzene, Isolute ENV+ SPE cartridge (Biotage, Charlotte, NC) was conditioned with 10 mL of acetonitrile followed by 10 mL of milli-Q water at a flow rate of approximately 5 mL min^{-1}. Each sample was acidified to pH 2 using 12 M HCl, and drawn through the SPE cartridge at a flow rate of approximately 1 mL min^{-1}. The adsorbed AEOs were eluted into 12-mL glass scintillation vials using 7 mL of acetonitrile at 1 mL min^{-1}. Each extract was subsequently evaporated to dryness under a stream of N_2, assessed by constant weight, and reconstituted in 3.0 mL of acetonitrile. This 3.0 mL extract volume was partitioned into 1-mL aliquots and a single aliquot was examined by ESI-HRMS and, after conversion to the methyl esters, a second aliquot by GC × GC-TOF/MS.

2.5. Infusion-Electrospray Ionization Mass Spectrometry. Low resolution ESI-MS analyses[32] for NAs were conducted with a Quattro Ultima (Waters Corp., Milford, MA) triple quadrupole mass spectrometer equipped with an ESI interface operating in negative-ion mode. The MS conditions were set as follows: source temperature 90 °C; desolvation temperature 220 °C; cone voltage setting 62 V; capillary voltage setting 2.63 kV; cone gas (N_2) flow rate 158 L h^{-1}; desolvation gas (N_2) flow rate 489 L h^{-1}. The multiplier was set at 650 V and full scan mass spectra were acquired in the m/z range 50−550. Samples (5 μL) were loop injected by use of a Waters 2695 separations module with 50:50 acetonitrile/water containing 0.1% ammonium hydroxide as the eluent at 200 μL min^{-1}.

Level-2 AEO profiling of sample extracts using ESI-HRMS was performed on a LTQ Orbitrap Velos mass spectrometer (Thermo Fisher Scientific, San Jose, CA) using electrospray ionization in negative ion mode. ESI source conditions were as follows: heater temperature was set to 50 °C, sheath gas flow rate was set to 25 (arbitrary units), auxiliary gas flow rate was set to 5 (arbitrary units), spray voltage set to 2.90 kV, capillary temperature was set to 275 °C and the S lens RF level was set to 67%. Samples were analyzed in full scan with an m/z range of 100−600, at a resolution set to 100 000 using the lockmass of m/z 212.07507 $[M-H]^-$ of *n*-butyl benzenesulfonamide. Resulting NA concentrations were determined by comparison to a predefined 5-point regression ($R^2 > 0.989$) of OSPW-derived NAs at known concentrations (initially quantified by FTIR). Xcalibur version 2.1 software (Thermo Fisher Scientific San Jose, CA) was used for data acquisition, instrument operation, and quantitative data analysis. Class distributions were determined using acquired accurate mass data and Composer version 1.0.2 (Sierra Analytics, Inc. Modesto, CA) with an average mass error for all classes of approximately 1 ppm, with an O_2 mass error of 0.065 ppm.

2.6. GC × GC-TOF/MS. Extracts selected for Level-2 AEO profiling by GC × GC-TOF/MS were evaporated to dryness under a stream of N_2, methylated by refluxing for 90 min at 70 °C with boron trifluoride-methanol (2 mL; Aldrich, Poole, UK), back-extracted into hexane (2 × 1 mL) and concentrated under a stream of N_2 to 50 μL. Conditions for analysis were essentially as described previously.[36] Briefly, analyses were conducted using

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Table 1. Level-1 Analyses for OSPW and Natural (Far-field) Groundwater Samples, Collected from the Shore of Rivers in the Oil Sands Area of the Athabasca River Watershed[a]

Associated surface water body	Sample type	Water type	Na:Cl (molar)	[Na] (mg L^{-1})	[B] (μg L^{-1})	[NH_4] (mg L^{-1})	[NA] (mg L^{-1})	SFS OSPW profile?
	OSPW 1	saline	2.5	636	2275	28.40	54	Y
	OSPW 2	saline	1.0	287	3164	1.30	60	Y
Athabasca R.	Drive-point 1	saline	1.7	1577	4040	0.84	48	Y
Ells R.	Drive-point 2	n/a	n/a	n/a	n/a	0.91	27	Y
Athabasca R.	Drive-point 3	fresh	1.4	1.8	68.7	0.18	<DL	N
Joslyn Cr.	Seep	fresh	22.6	6	15	n/a	4	N
Athabasca R.	Drive-point 7	sulfate	1.84	182	577	<DL	26	Y
Athabasca R.	Drive-point 8	fresh	1.80	52.6	126	16.2	20	N
Athabasca R.	Drive-point 9	saline	1.13	713	1620	0.57	33	Y
Athabasca R.	Drive-point 10	fresh	<DL	<DL	90.6	1.03	7	Y
Athabasca R.	Drive-point 11	fresh	0.76	4.3	66	0.17	4	Y
Athabasca R.	Drive-point 12	fresh	2.05	4.9	77.5	3.00	4	N
Ells R.	Drive-point 13	fresh	10.28	119	384	0.41	4	N
Ells R.	Drive-point 14	fresh-alkaline	11.91	135	435	0.03	5	N
Ells R.	Drive-point 15	sulfate	11.84	594	695	0.03	4	N
Ells R.	Drive-point 16	alkaline	2.40	680	1340	1.44	10	Y
Steepbank R.	Drive-point 17	fresh	6.62	3.4	126	0.17	5	n/a
Steepbank R.	Drive-point 18	fresh	0.00	<DL	67.2	0.09	5	n/a
Steepbank R.	Drive-point 19	fresh	0.00	<DL	77.7	0.07	4	n/a
Steepbank R.	Drive-point 20	fresh	2.96	4.8	217	0.04	n/a	n/a
Steepbank R.	Drive-point 21	fresh	0.00	<DL	125	<DL	6	n/a
Steepbank R.	Drive-point 22	fresh	0.00	<DL	204	0.03	n/a	n/a

[a]Y, observed. N, not observed. n/a, bitumen in sample prevented analysis for Drive-point 2; SFS not conducted for Drive-points 17–22; insufficient sample for NAs for Drive-points 20, 22. <DL, values less than method detection limit of 0.01 mg L^{-1} for Na; 3 mg L^{-1} for NAs; 0.02 mg L^{-1} for NH_4.

an Agilent 7890A gas chromatograph (Agilent Technologies, Wilmington, DE) equipped with a Zoex ZX2 GC × GC cryogenic modulator (Houston, TX) interfaced with an Almsco BenchToFdx time-of-flight mass spectrometer (Almsco International, Llantrisant, UK) operated in positive ion electron ionization mode and calibrated with perfluorotributylamine. The scan speed was 50 Hz, the first-dimension column was 50 m × 0.25 mm ×0.40 mm VF1-MS (Varian, Palo Alto, CA), and the second-dimension column was 2.5 m × 0.15 mm ×0.15 mm VF-17MS (Varian). Three μL of sample were injected in a splitless mode at 300 °C. The initial temperature of the oven (40 °C) was held for 1 min and then increased at 2 °C min^{-1} to 325 °C and held for 10 min. The modulation period was 4 s, the transfer line temperature was 280 °C, and the ion source temperature was 300 °C. Helium was used as the carrier gas at a constant flow rate of 0.8 mL min^{-1}. Subsequent data processing was conducted using GCImage v2.1 (Zoex).

3. RESULTS AND DISCUSSION

3.1. Profiling OSPW versus Natural Groundwaters. Differentiation between the 2 OSPW and the 20 natural groundwater (far-field) samples was first attempted in the Level-1 analyses that included geochemical data, total NAs, and the presence/absence of the SFS NA profile (Table 1). The SFS profiles of OSPW from the two mining operations studied (Figure 2) were consistent with those obtained in previous analyses.[16,31] Concentrations of total NAs in the OSPW samples were 54 and 60 mg L^{-1}, consistent with values previously reported for OSPW.[42] In previous studies,[24,29] 30 mg L^{-1} and 40 mg L^{-1} were used as the lower NA concentration limit to identify OSPW-affected water. However, one study[43] identified OSPW with NA concentrations below 10 mg L^{-1}.

Of the 14 far-field samples analyzed by SFS, 7 had spectral profiles similar to those of OSPW, although Drive-points 7 and 11 differed in that they exhibited lower signal intensities at 282 nm and elevated signal intensities at 320 and 345 nm (SI Figure S1). While the majority of the far-field samples in the current study had lower NA concentrations than OSPW (<10 mg L^{-1}), Drive-point 2, on the Ells River, contained 27 mg L^{-1} and 4 samples from an area along the Athabasca River where the McMurray Formation outcrops at the river edge (near Drive-point 1; Figure 1) ranged from 20 to 48 mg L^{-1}. Generally, appreciable NA concentrations corresponded with the presence of the SFS profile for OSPW, and vice versa, but there were a few exceptions which are currently under investigation: Drive-point 11 had a positive SFS profile and NA concentration of 4 mg L^{-1}, and Drive-point 8 had a negative SFS profile and a NA concentration of 20 mg L^{-1} (Table 1). The occurrence of an SFS profile similar to that observed for OSPW in many far-field samples with appreciable NA concentrations illustrates that these parameters are effective at identifying the presence of bitumen-derived AEOs, however they alone cannot be used to indicate whether these AEOs are originating from natural or OSPW sources.

A full description of the geochemical comparisons between far-field groundwater and OSPW is provided in SI Geochemistry. Briefly, analysis of the geochemical data showed that the ranges of most parameters (Na, B, and NH_4 concentrations, Na:Cl ratio) from the 20 far-field samples encompassed those for OSPW in this study (Table 1). When plotted on a Piper Plot (Figure 3A), the far-field samples plotted across all water types (alkaline, saline, sulfate, fresh), whereas the OSPW samples in general were commonly of alkaline or saline water type.[24,25,29,43] These results are consistent with previous conclusions that geochemical parameters alone cannot broadly distinguish OSPW

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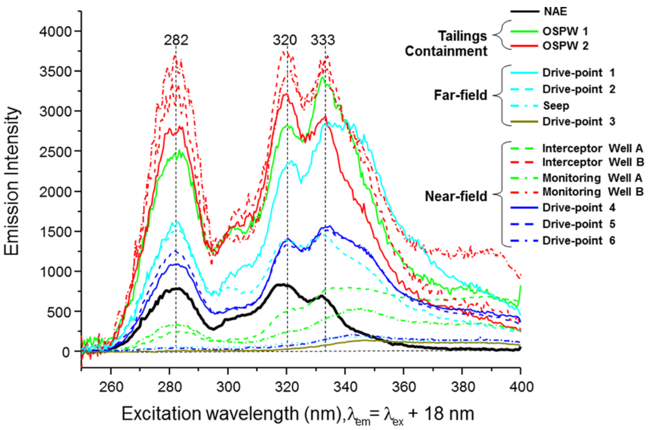

Figure 2. Spectra from synchronous fluorescence spectroscopy (SFS) for Near-field, and Far-field samples, as well as for a naphthenic acid extract (NAE) isolated from "fresh" OSPW.

from bitumen-influenced natural groundwaters in the oil sands region.

Due to the qualitative nature of the data obtained from the SFS analysis, a rigorous principal component analysis could not be performed to assess the ability of the entire Level-1 analyses to distinguish OSPW from natural groundwaters. However, it is clear (Table 1; SI Geochemistry & SI Figure 1) that OSPW tends to be elevated in concentrations of Na, B, NH_4, and NA, as well as the characteristic SFS spectra for suspected oil sands aromatic organic acids). Several of the far-field samples (Drive-points 1, 9, and 16) have a similar composition, especially when considering dilution effects on OSPW-affected groundwater. Thus, while a combination of the Level-1 parameters does not provide a universal indicator for OSPW migration, they have been found to be useful as site-specific tracers (i.e., tracking known plumes)[26] where information on local groundwater chemistry and flow systems is available.[43]

The Level-1 analyses did, however, reveal multiple significant sources of naturally occurring bitumen-derived AEOs (Table 1). The Level-2 analyses then focused on profiling the complex AEO mixtures present in OSPW and natural sources by utilizing these new sources of natural AEOs from different hydrogeological settings. Drive-points 1 and 2 exhibited two of the highest NA concentrations and signal intensities of the SFS profile (Figure 2). The Drive-point 1 sample was collected from the top of the limestone layer in an area where bitumen-containing sands were exposed at the bank of the Athabasca River, and also had elevated levels of B and Na, as well as a saline-alkaline water type. The sample from Drive-point 2 was collected along the Ells River near an area designated for future oil sands mining development, but where no activities existed at the time of sampling. The extracted groundwater contained bituminous globules (note: filters clogged immediately preventing the collection of samples for major ion determinations). In this same general area, but on the smaller tributary of Joslyn Creek, a natural groundwater seep sample (Seep) was collected that also contained bituminous globules, but did not exhibit the SFS NA profile (Figure 2) and had low Na, B, and NA concentrations (fresh water type). Finally, the Drive-point 3 sample was collected off of the McMurray Formation and had low Na, B, and NA concentrations (fresh water type), and no SFS signature.

Level-2 analysis by ESI-HRMS of the AEO containing far-field samples provided relative contributions of various ion classes via heteroatom histograms (Figure 4), including those assigned to

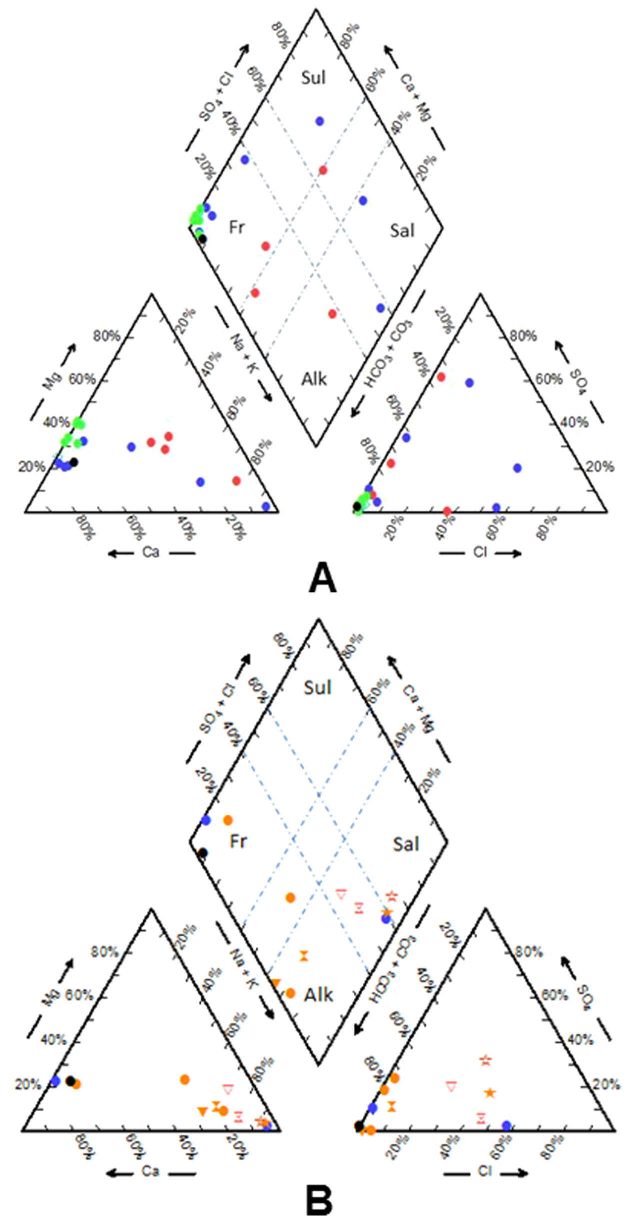

Figure 3. (A) Piper plot of major ions for natural far-field groundwater samples (>1 km from a tailings pond) collected along the Athabasca River (blue), Steepbank River (green), Ells River (red) and Joslyn Creek (black; seep) in the oil sands area. (B) Piper plot of major ions from the samples selected for Level 2 analyses, except for Drivepoint 2, separated by symbol type: OSPW (stars), interceptor wells (hourglass), on-development monitoring wells (triangle), and off-development drive-point or seep samples (circles); and by site/location: Site A samples in red outline; Site B samples in orange; background groundwater along Athabasca in blue; Joslyn Creek in black. Diamonds are divided (by dotted lines) into water type sections: Fr, fresh; Sul, sulfate; Sal, saline; Alk, alkaline (Hunter, 2001).

O_x, O_xS_y, N_xO_y, and $N_xO_yS_z$ species. For comparison purposes, the responses for all species were assumed to be the same in Figure 4, understanding that this assumption is not valid as ion-suppression and matrix effects are known to be prevalent for ESI-MS analyses of such complex mixtures. Furthermore, as authentic standards were not available for the thousands of components revealed by HRMS, these data are considered semi-quantitative. The O_x species in particular are of much interest as this group contains the classical NAs (O_2 components)

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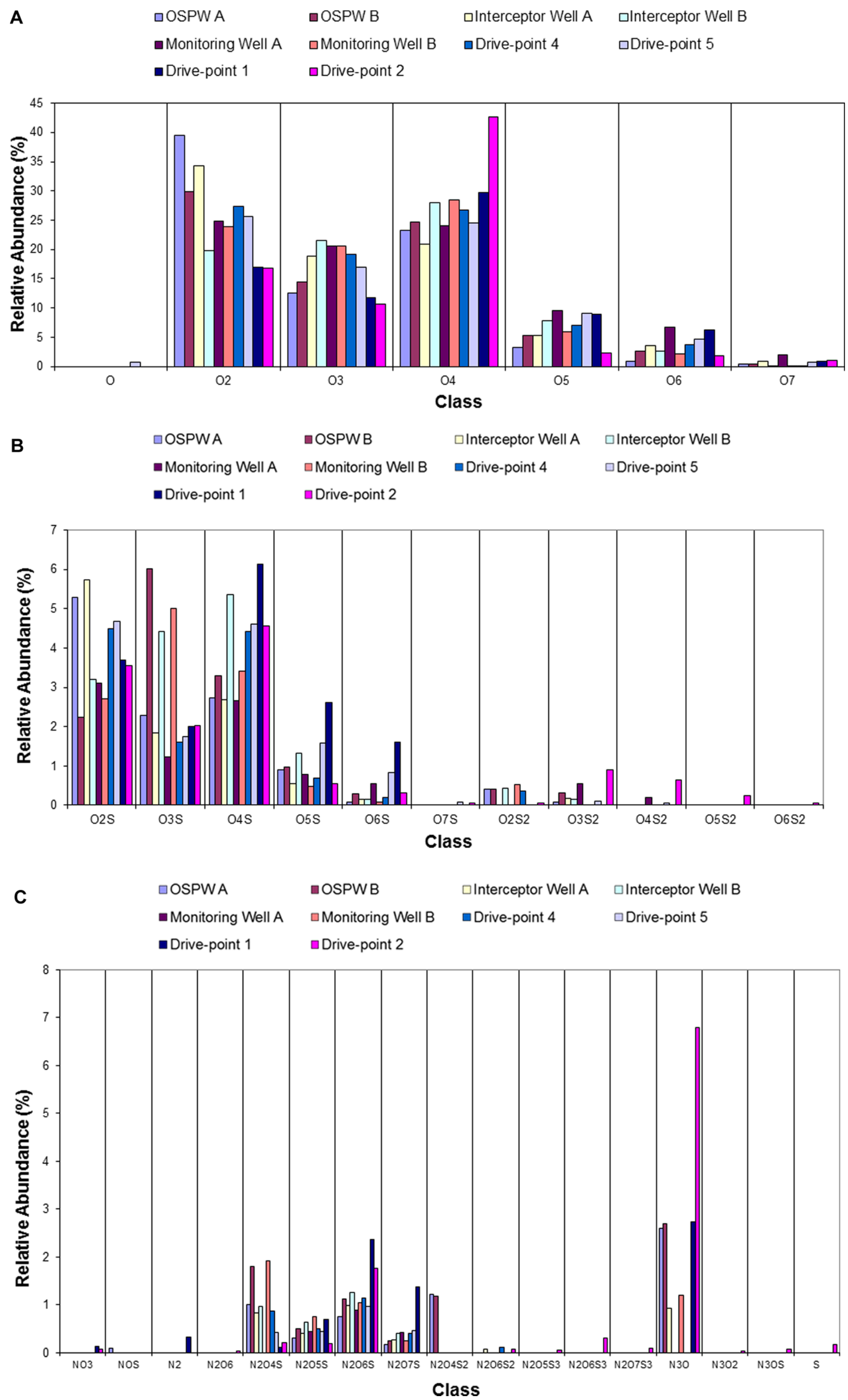

Figure 4. Level-2 HRMS speciation profiles for samples representative of On-development, Near-field, and Far-field samples.

along with higher oxidized hydroxyl acids (O_3 species), dicarboxylic acids (O_4), and possibly humic, fulvic, or weathered acids (O_{5-7}).

All far-field samples with detectable concentrations of NAs (Drive-points 1 and 2) were dominated by O_x heteroatoms, with notable observations concerning ratios of O_2:O_4 containing ion classes (Table 2; Figure 4a). OSPW samples 1 and 2 had O_2:O_4 ratios of 1.69 and 1.21, respectively, however, Drive-points 1 and 2 differed whereby the O_2:O_4 ratios were the lowest observed at 0.57 and 0.40, respectively (Table 2).

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Table 2. Summary of Level-1 and Level-2 data for all OSPW, Near-field and Select Far-field Samples[a]

		Level-1						Level-2		
		Water type	Na:Cl (molar)	[Na] (mg L^{-1})	[B] (μg L^{-1})	[NA] (mg L^{-1})	SFS OSPW Profile?	HRMS O_2:O_4	GC × GC-TOF/MS Monoaromatic acids? Family A	Family B
Tailings containment	OSPW 1	saline	2.5	636	2275	54	Y	1.69	7/7	Y+
	OSPW 2	saline	1.0	287	3164	60	Y	1.21	7/7	Y+
Far-field	Drive-point 1	saline	1.7	1577	4040	48	Y	0.57	1/7; peak #5	Y
	Drive-point 2	n/a	n/a	n/a	n/a	27	Y	0.40	2/7; peaks #1,5	Y
	Drive-point 3	fresh	1.3	2	69	<DL	N		0/7	N
	Seep	fresh	22.6	6	15	4	Y		0/7	N
Near-field Site A	Interceptor Well	saline	1.7	631	1230	60	Y	1.65	4/7; peaks #1,3–5	Y+
	Monitoring Well	alkaline	2.7	549	743	30	Y	1.04	5/7; peaks #1–5	Y+
Near-field Site B	Interceptor Well	alkaline	7.8	272	1469	39	Y	0.71	4/7; peaks #1–4	Y
	Monitoring Well	alkaline	33.0	359	1640	43	Y	0.84	5/7; peaks #1–5	N
	Drive-point 4	alkaline	14.0	300	1620	50		1.02	7/7	Y+
	Drive-point 5	alkaline	18.0	61	1380	55	Y	1.04	5/7;peaks #1–5	Y+
	Drive-point 6	fresh	5.8	16	170	5	N	0.92	0/7	N

[a]Y, Observed for SFS, both Family B monoaromatic acids by GC × GC-TOF/MS at correct m/z and GC retention times. Y+ indicates enriched signal for Family B acids. N, Not observed for SFS or Family B monoaromatic acids at correct m/z and GC retention times. n/a, bitumen in sample prevented analysis. <DL values less than method detection limit of 0.01 mg L^{-1} for Na; 3 mg L^{-1} for NAs. O_2:O_4 ratios cannot be reported for NA <5 mg L^{-1}.

Ratios of O_xS ion classes, among others, have previously been proposed as useful diagnostic markers for OSPW in surface waters using Fourier transfer ion cyclotron resonance mass spectrometry (FTICR-MS).[19] In the current investigation, the increased prevalence of O_2 over O_4 species in OSPW samples and the reversal in the natural far-field samples appeared to be similarly reflected in the O_2S:O_4S ratios at these sites (Figure 4B), however the trend was less consistent. Although the sample set in this investigation only included two samples each of the anthropogenic and natural sources that contained appreciable concentrations of NAs, the diagnostic potential observed for the O_2:O_4 ratio is nevertheless consistent with suggestions from previous work using ESI-HRMS[19,33,38] and supports use of this ratio in tracking OSPW.

Qualitative analysis by GC × GC-TOF/MS focused on two groups of well-resolved acids previously suggested to be monoaromatic steroidal-type acids,[31] using base peak or characteristic ions (Family A m/z 145; Family B m/z 237, 310). Analysis of the two OSPW samples revealed strong signal intensities for both families, consistent with previous analyses of NAs extracted from OSPW by GC × GC-TOF/MS.[31] Seven distinct Family A members were identified by retention times (R1 ± 0.1 min, R2 ± 0.2 s) that were used in profiling (Peak 1: R1−113.2 min, R2−2.8 s; Peak 2: R1−114.2 min, R2−2.6 s; Peak 3: R1−117.0 min, R2−3.0 s; Peak 4: R1−118.7 min, R2−3.0 s; Peak 5: R1−120.3 min, R2−3.1 s; Peak 6: R1−122.9 min, R2−2.4 s; Peak 7: R1−123.5 min, R2−2.4 s) and two distinct Family B compounds were similarly identified (m/z 237: R1−106.2 min, R2−1.4 s; m/z 310: R1−106.5 min, R2−1.5 s) (Figure 5). In contrast, Drive-points 1 and 2, the far-field samples with appreciable NA concentrations and SFS signal intensities approximating OSPW (Figure 2; Table 2), exhibited only 1 or 2 of the 7 Family A isomers, and comparably minimal signals for Family B. The remaining two far-field samples (Drive-point 3 and Seep) lacked any signal for both families under the conditions used (Table 2). Acids with structures similar to those of Families A and B are suspected as contributors to the 282 nm maximum in the SFS profile,[31] however, the present results indicate that different monoaromatic acids are contributing to the SFS profiles within the far-field samples. While lack of authentic reference compounds and limited sample volumes in the present study precluded definitive identifications of these acids, their potential as tracers of OSPW migration is certainly indicated. Work is underway to better characterize the structures of these compounds and to establish their relevance for monitoring migration of OSPW.

3.2. Profiling Groundwaters near Tailings Ponds. The Level-2 profiling analyses were then applied to a series of groundwater samples collected near two previously studied tailings ponds, to determine if their profiles more closely resembled OSPW or natural bitumen-derived AEOs. Samples were collected from near-field on-development interceptor and monitoring wells near tailings ponds A and B, as well as from shallow drive-points along the bank of the Athabasca River, within 200 m of tailings containment B (Figure 1). Although it cannot be assumed that any of these samples contain OSPW, they were collected in areas where previous studies have suggested OSPW impacts on local groundwater (Site A;[26] Site B [24]) as determined by Level-1 analyses similar to those employed in this study.

Analysis by ESI-HRMS of the two Site A samples revealed O_2:O_4 ratios of 1.65 and 1.04 for Interceptor well A and Monitoring well A, respectively, closely resembling the 1.29 and 1.61 ratios measured for OSPW (Table 2; Figure 4A). The somewhat lower ratio for the Monitoring well, as well as a lower NA concentration (Interceptor well A: 59.8 mg L^{-1}; Monitoring well A: 29.7 mg L^{-1}) indicates that the sample may have contained a mixture of OSPW and natural groundwater-derived NAs. Moreover, all Site A samples fell within a similar zone on a Piper plot (intermediate between alkaline and saline; Figure 3B).

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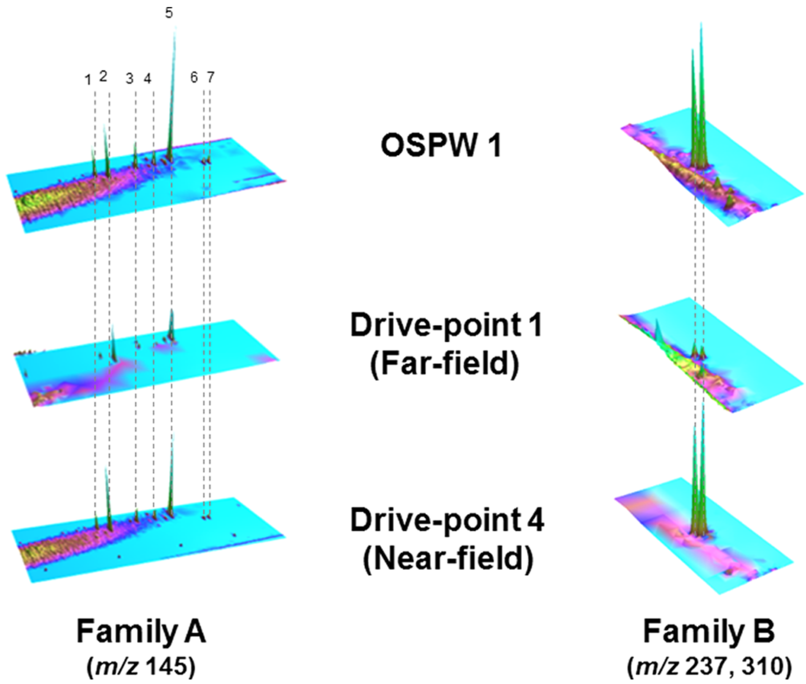

Figure 5. GC × GC-TOF/MS ion chromatograms for selected samples from OSPW, Far-field (Drive point 1) and Near-field (Drive-point 4) sites. Shown are the monoaromatic m/z 145 (Family A) and m/z 237 and 310 (Family B) ions; refer to Experimental for exact retention times.

Analysis by GC × GC-TOF/MS of the interceptor and monitoring well samples from Site A revealed 4 and 5 of the 7 diagnostic m/z 145 isomers (Family A), respectively, and enriched signal intensities for the m/z 237 and 310 ions (Family B) for both samples (Table 2). Qualitatively, both on-development samples were identical, with the exception of peak 2, which was absent from Interceptor well A. This, together with the enriched intensities of Family B ions, is consistent with both of the OSPW samples and contrasts with all of the far-field samples. Collectively, the Level-1 and Level-2 analyses all demonstrate a close similarity between these two Site A samples and OSPW, as opposed to the natural far-field groundwater. Consequently, both samples likely contain differing proportions of OSPW, with greater dilution from other water sources in Monitoring well A.

Consistent with both OSPW samples (and near-field Site A samples), GC × GC-TOF/MS analysis revealed that most of the Site B near-field samples exhibited enriched Family B aromatic acid signal intensities. With the exception of Drive-point 6, all Site B near-field samples consistently contained at least 4 out of the 7 Family A isomers, with peaks 6 and 7 being absent from all but one sample. It is worth noting that Drive-point 4 was the only non-OSPW sample of this study where all 7 Family A isomers were detected. There were no detectable signals for either ion Family for Drive-point 6 (Figure 5), suggesting it was not affected by OSPW. Furthermore, Level-1 analyses for this sample showed very low Na, B, and NA concentrations, no SFS signal, and a fresh water type (Table 2), in contrast to OSPW, supporting this contention. Monitoring well B was an exception where Family B ions were not detected, and while Interceptor well B exhibited these ions, they were at much lower intensities than both OSPW and near-field samples containing appreciable concentrations of NAs.

Level-2 profiling by ESI-HRMS of Site B near-field samples was also consistent with OSPW. Drive-points 4 and 5 had appreciable NA concentrations and O_2:O_4 ratios near 1.0, compared to 1.2 for Site B OSPW. The Interceptor and Monitoring well samples for Site B exhibited O_2:O_4 ratios of 0.71 and 0.84, respectively (Table 2; Figure 4A). These values, although lower than other near-field and OSPW samples, were greater than the two far-field samples with appreciable NA concentrations. It is important to understand that water collected in interceptor wells may emanate from a variety of sources (e.g., OSPW seepage, natural groundwater, surface runoff, etc.) that are mixed in unknown proportions with temporal fluctuations. It is therefore expected that interceptor systems will have a broad range of values that should lie between the range described by OSPW and the natural far-field samples.

When comparing the HRMS data for all Level-2 analyses, several trends are evident. First, the AEO profiles for O_2 and O_4 species are skewed to the left (OSPW influence) and right (natural bitumen-derived) respectively, whereas the profiles for the O_3, O_5, O_6, and O_7 components are bell shaped (Figure 4A). Although the rationale for these differences is not established, the relative abundances of the species may be linked to differences in the primary sources of these component classes. The relative abundances of the higher O_x species ($x > 4$; Figure 4A) were generally lower (<10%) compared to the levels of the O_2 and O_4 species (15−40%), and are likely indicative of the presence of weathered NAs and natural humic and fulvic acids. A complementary trend to that observed for the O_x species is also apparent for the O_xS_y species (Figure 4B), in which the profiles for the O_2S and O_3S species are skewed to the left (OSPW influence) whereas the O_4S, O_5S, O_6S, and O_4S_2 species are skewed to the right (natural bitumen-derived). These O_xS_y species are believed to contain natural surfactants, and possibly industrial additives, and warrant further investigation for their diagnostic utility as previously suggested.[19] While the profiles for the N-containing heteratomic species (Figure 4C) illustrate that some species classes are enriched (i.e., N_2O_4S, N_2O_6S, and N_3O), their application for source differentiation is unclear at present. Finally, although the O_2:O_4 ratio for the Drive-point 6 sample of 0.92 is suggestive of the influence of OSPW, the low NA concentration

(4.8 mg L^{-1}), coupled with the lack of detectable Family A and B acids and a fresh water type strongly indicates this is not the case and illustrates the importance of utilizing the Level-1 and 2 techniques in complement.

The results from the Level-2 analyses of the Site B groundwater samples containing appreciable concentrations of NAs (all samples except Drive-point 6, as noted above) are generally supported by the Level-1 analysis. All had elevated concentrations of B (1400−1600 μg L^{-1}) and NAs (39−55 mg L^{-1}) in a range similar to OSPW (Table 2), as well as exhibited the SFS signal characteristic of NAs. All were of similar water type (alkaline or alkaline-fresh), and Na concentrations were elevated, with the exception of the sample from Drive-point 5. Note that complete support for all of the Level-1 analyses was not expected, given the results on geochemical variation in background groundwater samples from this study, as previously discussed.

The chemical profiles of the Drive-point 4 and 5 samples more closely resembled those of OSPW than any of the far-field samples, particularly in the presence and distributions of the Family A and B acids. Previous work has relied on less definitive tracers, such as total NA concentrations and major ions,[24−26] or attributed differences in the chemical profiles of surface waters to groundwater inputs when the groundwater samples themselves did not exhibit an OSPW influence.[27] The fact that the sample from Drive-point 6 (not resembling OSPW) was collected within ~100 m of Drive-point 4 (strongly resembling OSPW), illustrates the inherent variability in groundwater geochemistry that can be expected given the convergence of local and regional flow systems along this river valley, where groundwaters with varying geochemical evolutions and characteristics may be encountered and combined with the potential localized effects of tailings structures and oil sands development. As such, future monitoring activities should give careful consideration to spatial replication of sampling in areas that may have highly variable and heterogeneous flow paths.

To investigate the potential for false-negatives, three samples (Far-field: Drive-point 3 and Seep; Near-field: Drive-point 6) were selected for detailed profiling. Rationale for their selection included that they exhibited lower concentrations of bitumen-derived AEOs ([NA] ≤ 5 mg L^{-1}), an absence of the characteristic SFS spectra for oil sands organic acids, and a "fresh" water type, in addition to the following: Drive-point 3 is located off of the McMurray Formation; the Seep sample contained bituminous globules, similar to Drive-point 2; and the proximity of Drive-point 6 to Drive-points 4 and 5 that exhibited bitumen-derived AEOs. Level-2 profiling confirmed that these three samples do not contain bitumen-derived AEOs, validating the absence of false negatives. Subsequent attempts to apply multivariate statistics to the differences reported in Table 2 were precluded by the qualitative data provided by the SFS and GC × GC-TOF/MS analyses.

3.3. Study Implications. The present investigation demonstrates that SFS, ESI-MS, and several geochemical analyses (Level-1 analyses) should not be used in isolation or in combination as a universal indicator of OSPW-affected groundwater, as these were unable to reliably differentiate OSPW from natural groundwaters containing bitumen-derived AEOs. However, data from ESI-HRMS and GC × GC-TOF/MS profiles (Level-2 analyses) for both sources appeared consistent within each source type, and different between them. Given the relatively small sample volumes utilized here for the Level-2 analyses (15−20 mL), these methodologies on their own likely would not enable conclusive differentiation of OSPW from all natural groundwater sources. However, the profiles provided by these methods, used in complement with the Level-1 analyses, collectively indicated that differentiation of sources was possible. This was highlighted by the Level-2 profiles of Drive-points 4 and 5 more closely resembling those of OSPW than any of the far-field samples, particularly in the presence and distributions of the Family A and B acids. The resemblance between the AEO profiles from OSPW and from 6 groundwater samples adjacent to two tailings ponds implies a common source, supporting the use of these complimentary analyses for source identification. These samples included two of upward flowing groundwater collected <1 m beneath the Athabasca River, suggesting OSPW-affected groundwater is reaching the river system. While profiling AEO mixtures from the Athabasca River was outside the groundwater focus of this study, the tools developed herein should provide this capability. Ongoing work with larger sample volumes is aimed at confirming and improving the diagnostic utility of the compound classes identified in this study.

■ ASSOCIATED CONTENT

Supporting Information

Figure S1 includes synchronous fluorescence spectra of all far-field samples. Geochemical criteria have been developed from past studies for differentiating OSPW from natural groundwater, these are briefly discussed and applied to the samples collected in this study. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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The battle over when and how to clean up oilsands tailing ponds is escalating

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An aerial view of Syncrude's oilsands upgrading facility and Mildred Lake settling basin tailings pond north of Fort McMurray. *RYAN JACKSON / EDMONTON JOURNAL*

Amid the bogs and forests of northern Alberta, in the heart of the oilpatch, lie some of the largest waste dumps of the global energy business.

In the shadow of the pipes and smokestacks that turn oilsands into flowing crude, earthen dams as long as 11 miles encircle lakes of toxic sludge, the byproduct of decades of extraction.

These tailings ponds represent perhaps the most serious environmental challenge facing the oilsands industry. Now, the battle over how quickly to clean them up — and fears about who will pay — is escalating anew.

To howls from environmentalists, the provincial energy regulator granted two industry giants — Suncor Energy Inc. and Canadian Natural Resources Ltd. — approval for plans (http://calgaryherald.com/business/energy/alberta-energy-regulator-to-reconsider-its-denial-of-suncors-tailings-clean-up-plan) that could push a full cleanup decades into the future. Critics say the industry could end up sticking taxpayers with the bill, estimated at $27 billion.

At issue is how, and by extension when, the ponds must be returned to a natural state. The industry is seeking more time to find cheaper ways to do the job. Environmentalists argue the problem has festered for half a century — and the waste keeps piling up.

“Rather than waiting for that silver bullet and continuing to test things out in the lab, we think that the technologies that exist today should be implemented in full force,” said Jodi McNeill, a policy analyst at the Pembina Institute, an energy researcher in Calgary.

Oilsands companies dispute the notion they’re dragging their feet. Suncor is approaching the cleanup with urgency, investing “significant resources and capital,” spokeswoman Sneh Seetal said. With the help of improved technologies, the company now can treat three times the tailings it produces in a year, helping shrink the backlog that’s built up over decades, she added.

Canadian Natural works to minimize environmental impacts and plans its land use with the end of the mines’ life in mind, spokeswoman Julie Woo said. The company already has reclaimed 378 hectares and planted more than 630,000 trees at its Horizon mine site since 2009, she noted.

RELATED

Big trucks, dead ducks put Alberta’s oilsands under environmental scrutiny (http://calgaryherald.com/business/energy/big-trucks-and-dead-ducks-put-albertas-oilsands-in-the-environmental-spotlight)

Dandelions found in oilsands tailings could help clean them up: researchers (http://calgaryherald.com/business/local-business/dandelions-found-in-oilsands-tailings-could-help-clean-them-up-researchers)

Q and A: Environmental engineering professor talks about treating water in oilsands tailings ponds (http://calgaryherald.com/business/energy/q-and-a-environmental-engineering-professor-talks-about-treating-water-in-oilsands-tailings-ponds)

For decades, tailings — a goopy mix of sand and chemicals — have been pumped into ponds so the solids could settle. But settling has taken longer than engineers expected. Result: Alberta’s tailings ponds cover about 97 square miles and hold 340 billion gallons of waste. That’s enough to fill more than half a million Olympic-size swimming pools.

The reservoirs attracted global attention in 2008 when about 1,600 ducks died (http://calgaryherald.com/news/politics/1606-dead-ducks-triple-the-trouble) in a Syncrude Canada Ltd. pond. Similar, though smaller, incidents have been reported occasionally since then, including the deaths of more than 100 birds near a Suncor tailings pond in September.

Tailings are treated using a variety of methods in combination, such as chemicals and centrifuges to speed the settling process. The final step, known as water capping, entails pumping the tailings into pits and covering the sludge with water.

Suncor has successfully transformed a tailings pond into a 220-hectare watershed capable of supporting plants and wildlife.

“That land is now a thriving ecosystem,” Seetal said, noting that bears and other animals have been spotted there. The company also has capped another pond with a layer of petroleum coke so vehicles can travel over it.

Still, provincial regulators estimate that cleaning up oil-sands facilities represents a $27 billion liability, of which the companies have posted only about $1 billion in security. Environmental groups say the cost could be much higher. The province also holds oil-sands assets against the liability. But McNeill says they are one of the highest-cost methods of producing crude, making them vulnerable to falling oil prices caused by a continued boom in American shale or the rapid adoption of electric cars.

Suncor heard similar concerns amid the oil-price downturn that started in 2014, and the company has shown it can prosper even with lower crude prices, Seetal said.

“We’re in this business for the long haul, and we have a history of being a responsible developer,” she said.

So far, the industry has spent about $12 billion on treating tailings and $50 million on research, according to Dan Wicklum, chief executive of Canada’s Oil Sands Innovation Alliance (http://www.cosia.ca/) . In addition to new filtration methods, the industry also is testing injecting carbon dioxide into tailings and running electrical currents through them to help the solids settle out more quickly, he said.

Vancouver-based MGX Minerals Inc. and PurLucid Treatment Solutions Inc. have teamed up to create a technology that filters tailings to produce lithium that could be sold for use in batteries. The Canadian government provided $8 million to scale up a pilot. One challenge is scaling such technology to handle the massive flow of tailings, Wicklum said. Another is finding a solution that’s economical and energy efficient. “We don’t want to solve one problem and exacerbate another.”

Time is short, according to Pembina’s McNeill, who characterized the tailings ponds as nothing less than an environmental emergency. “After 50 years, we’re still seeing the can kicked down the road.”

PolyMet Category 1 Waste Rock Stockpile

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December 10, 2015

These comments address the proposed method for the permanent disposal of Category 1 waste rock from the copper nickel mine proposed by PolyMet. These comments are derived from the material presented in the Final Environmental Impact Statement (FEIS) and referenced reports, which analyzed the impacts from the proposed PolyMet mine.

The long-term performance of the Category 1 waste rock stockpile is dependent on a water collection system composed of a cutoff wall surrounding the 526-acre 240-foot tall pile, and a drainage system within the cutoff wall. The cutoff wall is to be made of compacted soil, soil and bentonite, or a geomembrane placed on top of bedrock. Whatever materials are used, this cutoff wall is to have a hydraulic conductivity of less than 10E-5 cm/s. Additionally, a drainage system is to be installed inside of the cutoff wall to collect any water seepage or runoff from the pile. The drainage system is to be set on bedrock and covered with gravel. Any water collected by the drain is allegedly to be transported by gravity to pumps at the NE or SW corners of the pile, and then pumped to the Waste Water Treatment Facility for treatment prior to being pumped to the tailings basin at the plant site.

In addition to the water collection system, a geomembrane is to be placed on top of the entire Category 1 stockpile. The 40 – 60 mm membrane is intended to substantially reduce any infiltration into the rock pile. The geomembrane is to be covered by two layers of soil to protect the membrane from degradation.

The Category 1 stockpile was modeled using MODFLOW to estimate the effectiveness of the proposed collection system in collecting water and reducing the discharge of any contaminants generated in the rock pile. The modeling was performed over a 200-year period of time using data inputs from field investigations and estimated parameters for the water collection system and the geomembrane cover. The results of this modeling effort, which is presented in the FEIS, suggest 91 - 99% of the available water would be collected by the proposed collection system.

The collection efficiency of the proposed Category 1 collection system is extraordinary, but the system as modeled in MODFLOW is not a sound basis for making decisions. The gravity driven drainage system for moving collected water to the NE and SW corners of the stockpile with subsequent pumping to the WWTF will not work as currently proposed. The bedrock surface is uneven and not uniformly sloped, as noted in Fig. 4.2.2-6 of the FEIS. Consequently, a significant number of pumps stationed around the perimeter of the stockpile will be necessary. How these pumps will be maintained over a lengthy performance period of several hundreds of years is not easily prescribed. The conductivity of the cutoff wall for the Category 1 facility is quite high. The details for selecting the inputs of the MODFLOW model were not included in the FEIS, but the modeled facility must have been largely dependent on the drainage system for the high collection efficiency. However, the proposed drainage system is unlikely to work as anticipated.

The effect of freeze thaw and other degradation mechanisms on the long-term performance of the cutoff wall have not been fully considered in the modeling. The degradation of the cutoff wall over hundreds of years is a certainty, but the consequences are not established.

Finally, the supporting references to the FEIS provide an analysis of the geotechnical stability of the mine site. This analysis has the slopes of the facility defined by the angle of repose for the materials included in the Category 1 stockpile. The geotechnical stability of the Category 1 stockpile is significantly affected by the expansive geomembrane on top of the rocks but underneath the overlying cover soils. Presuming the overlying soils remain in place for hundreds of years is an unrealistic assumption given the presence of the geomembrane.

The modeling of the Category 1 Stockpile keeps the physical parameters for the facility as constant values through the time period of modeling, with the exception of the transition from active treatment to long-term mechanical treatment around mine year 50. Following the transition to mechanical treatment of collected water, the physical parameters remain constant for the remainder of the modeling period. As a consequence the degradation mechanisms for the collection system are not addressed. This leads to conclusions that are optimistic and not representative of the long-term performance of the collection system.

The optimistic characterizations of the long-term performance of the Category 1 Stockpile facility render the projections in the FEIS unsound for making decisions.

On page 5-37 of the FEIS statement is made that there is no evidence to suggest bedrock faults or fracture zones that provide enhanced groundwater flow to the Partridge or Embarrass Rivers. The FEIS fails to make any reference to or the information to be derived from the Dunka Pit mining operation that is just to the east of the proposed PolyMet mine. The Dunka Pit clearly shows significant fractures in the high wall of the pit. The integrity of the analysis presented in the FEIS is diminished for failing to acknowledge the available information from the Dunka mine.

Also on page 5-37 in the FEIS, the presence of buried channel deposits is acknowledged. The location of these buried channels is unknown. So, the analysis elects to treat the buried channel as a probabilistic increase in conductivity. A much more representative approach to treating these buried channels is to allow them to be present with the notion of there being a few for every spatial block and have the channels be significant conduits for transport of material. The number of channels in each spatial block could then be treated as a probabilistic value.

The analysis presented in the FEIS of the long-term performance of the Category 1 stockpile does not present the expected environmental impacts that can be attributed to the facility. At a minimum, additional analyses should be performed to properly represent the long-term impacts from the facility.

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Senior Research Scientist, Energy Division (2000 – 2001), Environmental Sciences Division (2001 – 2008). Research in waste management and safety analysis, preparation of Environmental Impact Statements for energy related projects.

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Program Manager, Waste Management and Safety Analysis Program, Center for Energy and Environmental Analysis, Energy Division. Manager of Division work in radioactive, hazardous, industrial, and mixed waste management and safety analysis. Major activities include performance assessment and safety analysis reports for DOE sites.

1989 – 1997 OAK RIDGE NATIONAL LABORATORY

Research and Development Group Leader, Applied Physical Sciences Group, Environmental Analysis and Assessment Section, Energy Division. Manager of Section work in radioactive waste management and safety analysis. Focus of research was on geologic and hydrologic analysis. Preparation of performance assessments fpr DOE low-level radioactive waste disposal facilities. Conduct of site-specific analyses for waste management, Safety Analysis Reports, Environmental Restoration, and Environmental Impact Statements. Manager of a staff of 7 with a budget of $2 million.

1982 – 1989 OAK RIDGE NATIONAL LABORATORY

Research Staff, Energy Division. Preparation of technical analyses of water resource issues in radioactive waste management, in-situ uranium mining, uranium milling, synfuels technologies, and hydropower. Development of waste management strategies for Lockheed Martin facilities, performance of site characterization studies of low-level radioactive waste disposal sites. Preparation of Environmental Impact Statements and Environmental Assessments for energy related projects.

1977 – 1982 OAK RIDGE NATIONAL LABORATORY

Research Associate, Energy Division. Preparation of Environmental Impact Statements, Environmental Assessments, and environmental analyses of nuclear, coal, geothermal, and conservation technologies. Conduct research investigations in environmental monitoring, surface water hydrology, and groundwater hydrology using theoretical, numerical, and field methods.

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Research/Teaching Assistant. Performance of laboratory research in the field of tire mechanics, Instructor for rigid body dynamics, statics, strength of materials, and advanced numerical analysis.

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Professional/Academic Honors

Pi Tau Sigma, Mechanical Engineering Honor Fraternity, 1969
Registered Professional Engineer,
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Significant Event Award, Martin Marietta Energy Systems, 1991
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Board Certified, American Academy of Environmental Engineers, 1996 – 2007
In Appreciation, American Society of Civil Engineers, Environmental Engineering Division, 1992
In Appreciation, American Society of Civil Engineers, Environmental Engineering Division, 1999
Certificate of Appreciation, Defense Logistics Agency, Department of Defense, 2005
Who's Who in Science and Engineering, 2007
Who's Who in America, 2007
Who's Who in the World, 2007
Retirement Certificate, Oak Ridge National Laboratory, 2008

Professional Activities

Reviewer, American Society of Civil Engineers, Hydraulics Division (1982 – 1996)
Reviewer, Elsevier Publishing Co. (1987)
Reviewer, Nuclear and Chemical Waste Management (1986 – 1995)
Member, American Society of Civil Engineers
Member, American Society of Mechanical Engineers
Member, Sigma Xi
Member, DOE Waste Classification Working Group, 1987
Member, DOE Task Force on Uranium Waste Problems, 1988
Member, DOE Low-Level Radioactive Waste Technical Resource Group for 40 CFR 193, 1988
Member, DOE Low-Level Radioactive Waste Peer Review Committee for DOE Order 5820.2A, 1988 – 1997
Member, DOE Performance Assessment Technical Resource Group for DOE Order 5820.2B, 1994 – 1995
Member, DOE Federal Facilities Compliance Act Disposal Work Group, 1994 – 1996
Member, DOE Defense Nuclear Facilities Safety Board Recommendation 94-2, Site Assessment Team, 1995
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Member, DOE Defense Nuclear Facilities Safety Board Recommendation 94-2. Working Group Assessment Team, 1995
Member, DOE Order 435.1 Revision Team, 1996 – 2000
Adjunct Associate Professor, North Carolina State University, Department of Mechanical and Aerospace Engineering, 1987 – 2000

Ph. D. Dissertation Committee Co-Chairman, North Carolina State University, Department of Mechanical and Aerospace Engineering, 1987 – 1993

Secretary, Air and Radiation Management Committee, Environmental Engineering Division, American Society of Civil Engineers, 1989 – 1990

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Secretary, Programs Committee, Environmental Engineering Division, American Society of Civil Engineers, 1992 – 1994

Member, American Society of Civil Engineers Task Committee on Mixed Waste, 1988 – 1993

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Chair, Professional Activities Committee, Environmental Engineering Division, American Society of Civil Engineers, 1996 – 1999

Secretary, Conference and Exhibits Council, Environmental and Water Resources Institute, American Society of Civil Engineers, 2001 – 2003

Member, Conference and Exhibits Council, Environmental and Water Resources Council, American Society of Civil Engineers, 1999 – 2001, 2003 – 2005

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Conference Chairman, 2002 Joint CSCE/ASCE International Conference on Environmental Engineering, Niagara Falls, Ontario

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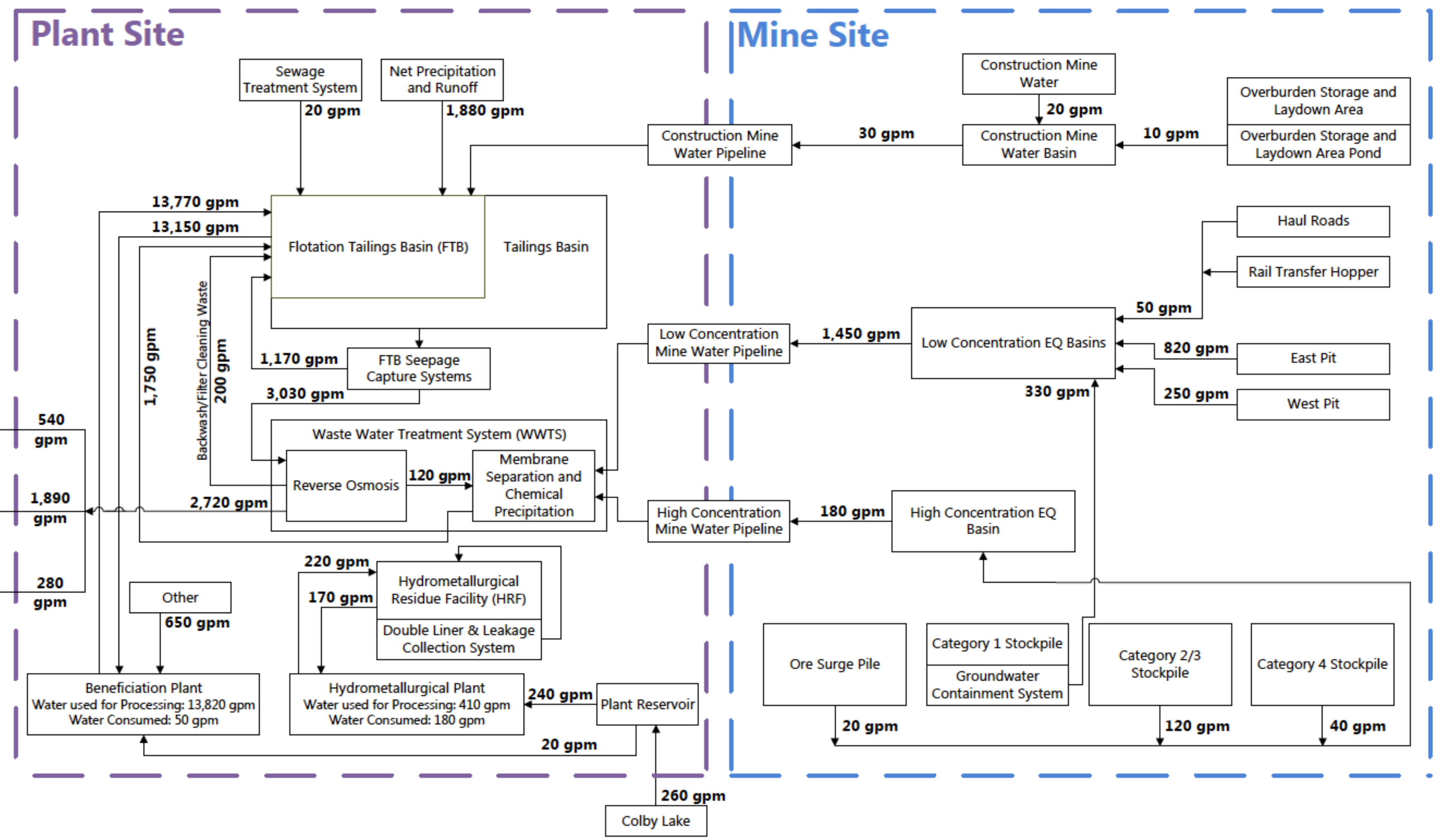
PolyMet Permit to Mine Application (Dec. 2017) pdf 405, Figure 11-5



Legend

XX → = Approximate Water Flow in Gallons Per Minute (gpm)

Notes:
1. This figure is not a comprehensive water balance. For clarity, it shows flows that are key to the NorthMet Project's overall water use strategy, and omits flows such as some inflows due to net precipitation and outflows due to potential liner leakage and other potential losses. Because not all flows are shown, and because flow rates are rounded to the nearest 10 gpm, total flows may not equal the sum of their contributing parts.
2. Flows provided are estimated average annual flows for Mine Year 10.
3. Water flows are based on the Water Modeling Data Package – Mine Site, Version 14 (February 2015) and the Water Modeling Data Package – Plant Site, Version 11 (March 2015), included in Appendix 16 of the application.

PROJECT WATER BALANCE IN MINE YEAR 10
NorthMet Project
Poly Met Mining, Inc.

Figure 11-5
Permit to Mine Application

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Message

From: Olson, Michael (DNR) [/O=MMS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=OLSON, MICHAEL (DNR4C96FCD1-0B4B-4AF7-BAAA-FFB6973C9B80]
Sent: 2/28/2013 10:01:05 AM
To: Kunz, Michael (DNR) [michael.kunz@state.mn.us]
Subject: FW: PolyMet Tailings Wet Closure

FYI

From: Donald Sutton [mailto:sutton@spectrum-eng.com]
Sent: Monday, January 23, 2012 11:52 AM
To: Dostert, Dana M (DNR)
Cc: Arkley, Stuart (DNR); Engstrom, Jennifer N (DNR); Olson, Michael (DNR); Wenz, Zach (DNR); Boyle, Jason (DNR); 'Ross Vellacott'; 'Jeff Coffin'; 'Schwanz, Neil T MVP'; 'Bryan Ulrich'
Subject: RE: PolyMet Tailings Wet Closure

Dana
I reviewed the documents you and Stuart provided. I share your wet closure concern and have additional concerns related to the long term tailings wet closure uncertainties and risks. I don't have many comments on the Barr documents other than thinking that the bentonite amended dam face and interior slopes will be subject to faster erosion if more precipitation runs off and less infiltrates. This could lead to other erosion problems, especially on the outside, because the slope geometry is geomorphologically unstable and the sandy matrix invites erosion. Can the soil cover become saturated and slide off the bentonite? I think the bentonite cover will eventually deteriorate due to erosion and plant roots and become ineffective, and that the erosion will weaken and destroy the embankments. If air is permitted to enter the tailings, they will oxidize and the purpose of the wet closure with bentonite seals will be negated. In my opinion, the reclamation plan is not a stable permanent closure.
Regarding the stockpile foundation settlement, my only concern is that they make sure that leachate from the piles flows to manageable collection points and doesn't leak. It would be helpful if any leakage reported to the open pits, because then it could be collected and treated with the other mine water discharge.

I've been thinking about alternative closures for the tailings basin, how closures might be designed, and how surface water and leachates would be permanently managed. I believe the purpose of the wet cover is to inhibit or prevent sulfide oxidation and the generation of sulfates, but as I discuss later, PolyMet's proposal may not completely prevent oxidation and infiltration if the bentonite seal is not installed properly or after it erodes away, so water collection and treatment may still be needed depending on the sulfide/sulfate content. If there is a reasonable risk that the wet closure won't prevent oxidation or sulfates for 900 years and if perpetual water collection and treatment will be needed, then why not investigate some dry closure options and compare the long term O&M costs and long term risks of each alternative? Perhaps there is a dry closure alternative that is more economical and less risky when perpetual maintenance O&M are considered. At some point, the cost of the risk will need to be assessed.

The challenge is to predict the amount and rate of sulfate generation for each alternative, how it will be collected and treated, and estimate how long sulfates will be generated depending on the oxidation rate, the infiltration rate, and the initial sulfide type and concentration. What is the maximum acceptable rate sulfate can be permitted to escape the site? This might tell us how long PolyMet or the State needs to collect and treat before the source is consumed and the pile of tailings becomes geochemically benign. If we are considering a 900 year life, I suspect that if the sulfides oxidize and flush out that eventually the source will dissipate and there will be no more contaminants. After the sulfides/sulfates have dissipated to an acceptable level, what is the remaining risk? The PolyMet plan attempts to minimize the sulfate generation rate, which will require a longer time before the sulfides and sulfates are flushed out. What about flipping the logic around and maximizing the sulfate generation rate (oxidation rate) to minimize the length of time this problem will persist? If water must be collected and treated for both cases, then which one will be more economical?

In its simplest form, the proposed tailings basin will be a big pile of highly erosive loose sand and silt. The wet closure will include a pond of water on top that saturates the sand/silt making it less stable and more likely to fail than the dry option. For a wet closure to remain geotechnically and geochemically stable until 2900, the water level and infiltration rates must be perpetually regulated, and the embankments and water management controls must be perpetually inspected and repaired. In the Tailings Basin Reclamation summary in NorthMet Project Description, p73/115, the anticipated perpetual maintenance items include: maintaining the pond no closer than 625 feet from the interior edge of the dams, pumping water from Colby Lake to maintain the pool level, recycling seepage back to the pond or sending it to a water treatment plant to reduce the sulfates to 10 ppm. It is assumed that eventually the pond water level will stabilize and the sulfate level will become less than 10ppm, but the document doesn't explain how they come to this conclusion. Surplus storm water will be directed through "clog resistant" lined/revegetated or riprapped channels or pipe outfall structures. Oxidation of the tailings will be prevented by placing a layer of bentonite 30 inches below the surface of the dams and beaches. Bentonite will be placed on the pond bottom to minimize infiltration.

I envision that PolyMet's reclamation plan could work for a while, but don't see how it will function forever without falling apart unless it is continuously maintained; which is a major leap of faith. The wet closure will require perpetual maintenance and water management to control the water level in the pond, to collect and treat seepage, and to maintain the dam embankments and the flood control structures, pipes, etc.

We are assuming that the geotechnical modeling reasonably reflects expected conditions into perpetuity, and that the model input variables are representative and reliable. We are trusting PolyMet's lab scale data for the tailings size consist and properties. If this were a dry closure, and the tailings were allowed to drain, then I wouldn't be so concerned, because mill tailings tend to be very rough and angular and can gain strength as they dewater and compact. Wet closure is different. I believe that the MSHA guidance assumes that at some point in time there will be a dry closure, and that the saturated conditions are only temporary.

In addition to seismic and geotechnical failure events, dam failures can be triggered by water related issues such as piping or erosion that weaken the structure over time, or catastrophic storm events that overwhelm the structures or gradually weaken them. What happens to these structures after decades or centuries of wet/dry, freeze/thaw cycles? Can they crumble or crack? Roots and vegetation can plug them. Water can leak under or around them and cause piping.

When we drove around the embankment perimeter in November, I could see that portions of the embankment were already eroding. The loose sandy embankment is not very resistant to erosion. What happens to the stability over time if the embankment becomes thinner due to erosion? Has anyone calculated the erosion rate of the outside embankment? If it loses 1 inch per year, then in 900 years it could be 75 feet thinner. How might that change the stability? What if it erodes 2 or 3 inches per year? I noticed some animal burrows. How far do they burrow? How far do they need to burrow before encountering the saturated zone? If there is a concentrated flow during a major run-off event, or if piping occurs there can be rapid and major erosion of the embankment that might allow the ponded water to escape. If the out-slopes are made impermeable (with a layer of bentonite), then run-off will be greater and erosion will more rapidly attack the embankment because less water will infiltrate and more will run off. During a thunderstorm there will be a lot of water coming down the outside that will cause erosion and saturate the 30" of fill above the bentonite, possibly resulting in a sliding failure, rills and gullies. Once the erosion begins, it can continue head cutting into the impounded water unless it is regularly repaired.

The climate is changing in unpredictable ways that makes it difficult to predict the water balance. For example, at the Zortman and Landusky sites in north central Montana, we have experienced three plus 100 year events in the last 10 years. In 2011, we experienced an event believed to be the 200 to 500 year event that overwhelmed all our water management and water treatment facilities and caused a waste dump to collapse and destroy a water capture and pump back station. The average precipitation for the last 2 years is 100 % above average. I don't know how the climate change will affect MN, but it is getting wetter in some areas and drier in other areas. If it becomes wetter or drier than anticipated how will it affect the closure water balance? How will it affect the saturation of the embankments or the erosion rates? How will it affect the storm water controls? What about wave erosion on the inside combined with wind and water and varmit erosion on the outside? More thunderstorms would cause more rilling and gullying. All the materials are highly susceptible to erosion, so more intense rainfall will cause faster erosion.

What happens if the bentonite doesn't seal the infiltration and the pond water drains out faster than anticipated, or if the climate is drier? How long does PolyMet intend to pump water from Colby Lake? If the Colby Lake pumping funding is used up, and the pond dries out, it essentially becomes a dry closure. I suspect their wet closure plan will only function within a narrow range of precipitation and leakage assumptions without perpetual pumping from the lake during dry periods and decanting surplus water during wet periods.

PolyMet's plan to recover as much sulfide as possible (including pyrite) to minimize the sulfide content in the tailings is a good idea. I know they can never get the sulfide level to zero, but is there some level that would be low enough that would meet the same standards as the low sulfur waste stockpile? If PolyMet spent more to clean up the tails, then perhaps there could be long term closure savings if the sulfide level was no longer an issue.

The environmental consequence of a failure depends on the amount of sulfate the local ecosystem can tolerate and the length of time the problem will persist. The amount of sulfate available after a failure depends on the initial sulfide content of the tailings, the rate the sulfide oxidizes to sulfates, the rate the sulfate is released from the tailings, and the elapsed time. All combine to control the remaining sulfide/sulfate that would be released after a failure. (PolyMet is proposing to recirculate the seeps – if they do that, then I assume the sulfate concentration would increase, which would create worse contamination if it all escaped at once).

If the sulfides oxidize and are gradually flushed out of the bottom of the tailings basin or into a seepage collection system and treated or discharged, then eventually the tailings will become relatively inert. How long will this take? Probably a long time if they remain sub-aqueous beneath a bentonite seal, but if the basin doesn't hold water and the tailings are allowed to rapidly oxidize or are forced to oxidize rapidly, it might become inert fairly rapidly.

Perhaps, rather than trying to prevent oxidation, there might be a way to accelerate the oxidation to minimize the collection and treatment time. Consider installing a leachate collection system in the taconite tailings basins before the new tailings are added. This might entail putting the bentonite on the existing surface and installing some type of under drain collection system before the tailings are placed on top. This alternative might be more economical than placing the bentonite on top of the tailings and maintaining everything forever. In this alternative, there would be no need for any type of low permeability cap – all the precipitation would be allowed to infiltrate. Some additional water management would need to be engineered so 100% of the precipitation doesn't report to the leachate, but there would be less need for elaborate storm control features other than some decants similar to those already installed in the taconite ponds to drain away any large storm events.

I was trying to imagine a dry closure design that would be geomorphologically stable. The challenge is to get the precipitation off the top without causing erosion. If the tailings are graded so that water runs off the interior, there will be a big risk of erosion and gullying in the sandy material unless the velocities can be kept low, which will be very difficult to achieve without substantial regrading or some type of a drop inlet decant structure. Lined channels might work for a while, but are likely to fail after several years if water gets under the liner. I imagine that the plus 100 year event flow rates will be considerable and the velocities quite erosive if the run-off is uncontrolled. Any type of impermeable cover system will be very expensive and will have trouble dissipating the run-off energy. The cover will eventually erode and unravel. A stable configuration may be to allow the precipitation to infiltrate and evaporate or evapo-transpire as it is doing today, but how do you deal with the leachate? Will the pond actually drain sufficiently to reduce the saturation levels, or will some type of permanent decant or central drain system be needed, similar to the existing system, to minimize the pool, reduce the area that is saturated, and reduce the quantity of leachate that must be captured and treated?

Geochemically, a wet closure is only practical if it permanently inhibits sulfate generation to a rate slow enough that no water treatment or collection is needed. If the wet closure does not prevent oxidation or if the oxidation of the fine grains occurs during milling or when the fine grained sulfides are exposed in the pond before being buried, then leachate will need to be collected and treated. In this case, wet closure may act geochemically similar to the uncovered dry closure, but may take longer for the sulfates to dissipate and be flushed out. If the wet closure successfully prevents oxidation and sulfate production, then a structural failure will release all the sulfides that will rapidly oxidize to sulfates, so the contamination event is only delayed, not prevented. When a wet closure failure occurs, the environmental damage my occur before the spill can be managed, especially if the sulfate concentration is high.

If seepage collection or treatment is or might be necessary for an indefinite time with a wet closure, then what is the benefit of wet closure? The wet closure is riskier, has more uncertainties, and may be more expensive because it will require more perpetual care and maintenance than a dry closure. I suggest that PolyMet investigate some alternatives. My preference is to look into installing an underdrain collection on the taconite so that only tailings leachate is collected and treated. I assume PolyMet already knows the sulfide content of the tailings under various recovery scenarios. They may need to run some additional grinding and flotation tests, but it would be useful if they could investigate the oxidation rate of the finely ground tailings when exposed to air, and to explore the amount of oxidation when treated with various oxidizers to determine if my idea about accelerating the oxidation has any merit. This might be something the geochemists should comment on first. I don't like the wet closure, because it is not a permanent closure. I believe it will eventually fail and release the sulfates.

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From: Dostert, Dana M (DNR) [mailto:dana.dostert@state.mn.us]
Sent: Thursday, January 19, 2012 10:11 AM
To: Donald Sutton
Cc: Arkley, Stuart (DNR)
Subject: RE: PolyMet

Hi Don,

Sorry that you couldn't get into the meetings as your expertise would have been valuable.

I sent out a list of questions prior to the meeting. Do you have any comments on those. Our Geochemists don't think there is a geochemical concern but there may be a physical one. Neil is going to provide some comments on my questions. If you could provide any comments to my questions and any of your own, that would be appreciated.

Thanks

Dana D.

October 12, 2017

Mr. Kevin Lee
Senior Staff Attorney
Minnesota Center for Environmental Advocacy
26 East Exchange Street, Suite 206
Saint Paul, MN 55101

Subject: Comments on Draft Dam Safety Permit 2016-1380 (Flotation Tailings Basin), Updated Permit Application Documents, and Outstanding Permit Issues

Dear Mr. Lee:

I am writing to provide my comments to the Minnesota Center for Environmental Advocacy (MCEA) regarding the subject draft permit for the NorthMet project. My comments, presented below, are based on my review of the draft permit, the NorthMet Dam Safety Permit Application for the Flotation Tailings Basin (PolyMet, May 2017), and the Template for Pilot/Field Testing of Bentonite Amendment of Tailings (PolyMet, April 2017). Please note that I also reviewed the Draft Dam Safety Permit 2016-1383 for the Hydrometallurgical Residue Facility, but I have no comments on this draft permit.

Comments on Draft Dam Safety Permit 2016-1380

1. Condition 31: Bentonite Testing:

   As stated in the Template for Pilot/Field Testing of Bentonite Amendment of Tailings (PolyMet, April 2017), the objective of bentonite amendment of the dams, beaches, and pond bottom are to limit oxygen infiltration into the tailings by reducing water infiltration and maintaining a continuous areal zone of saturation in the bentonite-amended layers. However, neither the permit application nor the pilot/field testing template specifies a requirement for the degree of saturation that must be maintained in the bentonite-amended dams and beaches. Also, the pilot/field testing template does not describe any laboratory QC testing that will be performed to verify the efficacy of the field mixing or the adequacy of the proposed 3 % granular bentonite amendment for meeting the design objective. According to Specification 03100 in Version 7 of the Flotation Tailings Management Plan (PolyMet, May 2017), laboratory test requirements should be part of the pilot testing plan. Finally, although the pilot/field testing template presents a list of considerations for field testing and describes various field testing and monitoring methods that "could" be used, the template provides only a conceptual level of detail for how the field tests may be carried out and does not specify the performance metrics that will be used to determine success or failure. Thus, the template, in its current form, falls short of being a field/pilot testing plan.

Based on the above, the DNR should require PolyMet to produce a field/pilot testing plan prior to initiation of field work. I recommend the following revision to Permit Condition 31:

> *"Prior to dam construction, Permittee shall prepare a pilot/field testing plan for the bentonite amendment that represents an expanded and more detailed version of the April 2017 Template for Pilot/Field-Testing of Bentonite Amendment of Tailings. This plan should clarify the design criteria for the layers, specify the laboratory and field testing methods that will be used to verify adequate mixing, placement, and performance in accordance with the design, specify how the field tests will be carried out (including testing/monitoring frequencies, locations, and installation details), and establish the performance metrics that will be used to determine success or failure of the pilot tests. Permittee shall obtain written approval from the DNR Dam Safety Engineer of both the pilot/field testing plan and a subsequent report of the results of the pilot/field testing. Construction may not commence until such written approval of both the plan and the report is obtained."*

The EOR Review Team expressed concerns over the adequacy of a 3 % bentonite addition and the effectiveness of injecting bentonite into the pond bottom for creating a reliable infiltration barrier. While I share these concerns, a more fundamental problem is the lack of a design basis to support the feasibility of these layers for meeting the project objective. For example, the primary objective of the bentonite-amended layers in the dams and beaches is to provide a barrier to oxygen migration into the tailings by maintaining a "continuous areal zone of saturation." However, the permit documents do not specify a required degree of saturation, no mix design work has been completed to justify the proposed mixture, and no moisture retention testing or unsaturated flow modeling has been conducted to assess what level of saturation can be realistically expected to be maintained in the field. It is not possible to achieve fully saturated conditions in these layers at the time of placement (even wet of optimum compaction is not likely to yield a degree of saturation greater than about 90 %), and the degree of saturation will be prone to decrease, rather than increase, over time. While I fully support the use of pilot/field testing to establish means and methods and demonstrate performance, PolyMet still needs to establish appropriate performance criteria and design the layers accordingly before conducting field trials.

This introduces another concern: it appears that PolyMet is basing the use of 3 % granular bentonite on the results of a single laboratory hydraulic conductivity test conducted on a trial mixture of 3 % bentonite-amended tailings, which are provided in Attachment D of the Flotation Tailings Basin Dam Safety Permit Application. Replicate tests should be performed to demonstrate reproducibility. Also, no backup documentation for this test (e.g., no table of head measurements versus time, no plot of hydraulic conductivity as a function of time or pore volumes of flow, no measurements of inflow/outflow balance, etc.) is provided. As a result, I was not able to examine the test data or check the accuracy of the calculations. The reported hydraulic conductivity ($\sim 1.5 \times 10^{-7}$ cm/s) is much lower than expected based on comparison with data available for similar mixtures in the geoenvironmental engineering literature (e.g., see Abichou et al. 2000). I remain concerned that a 3 % granular bentonite amendment will be too low to create a homogenous layer in the field that is free of zones containing no bentonite. Bench-scale tests need to be performed using materials with gradations representative of those anticipated for the bentonite-amended layers to determine the percentage of bentonite required to meet the design criteria.

PolyMet proposes to conduct monitoring and mini-experiments during the pilot/field tests to assess factors that may interfere with or degrade the maintenance of a continuous zone of areal saturation in the bentonite-amended tailings layers, including desiccation, freeze-thaw degradation, root penetration, and incompatibility with pond water. Although I support this approach, the template for the pilot/field testing provides only a conceptual level of detail for how the mini-experiments may be carried out. Also, most of these factors (desiccation, freeze-thaw, and pond water incompatibility, in particular) can and should be investigated first by laboratory testing as part of mix design work conducted prior to field testing.

PolyMet provides no evidence to support the claim that the proposed bentonite-amended tailings layers, over the long term, will not be susceptible to root penetration, or that placing these layers beneath a 30-inch vegetated layer will provide adequate protection against wet-dry or freeze-thaw cycling. These processes can create macropores (i.e., large scale features such as cracks and fissures) that alter the network of pores controlling retention and movement of water (and air) in barrier layers. These types of problems are well documented in a recent, peer-reviewed study by Benson et al. (2011).

Likewise, proof of concept for the bentonite pond bottom remains inadequate. PolyMet has proposed three possible subaqueous placement methods (i.e., broadcasting of bentonite granules or pellets, bentonite injection into the existing bottom, or placement of a geosynthetic clay liner over the existing bottom), none of which are supported by laboratory studies, field case studies of successful use on other projects, or any other type of feasibility assessment. What is the contingency plan if none of the three proposed methods prove to be feasible based on the field test results?

Lastly, there does not appear to be a sound technical basis for the specified maximum hydraulic conductivity of 10^{-6} cm/s for the bentonite-amended tailings layers to be placed on the FTB dam side slopes and beach areas. According to PolyMet, the bentonite-amended tailings are meant to act as an oxygen barrier. However, no evidence is provided to demonstrate that bentonite-amended tailings with a hydraulic conductivity of 10^{-6} cm/s will be effective as an oxygen barrier. Moisture retention testing and unsaturated flow modeling are needed to assess the performance of these layers.

2. <u>Condition 45: Future Closure Considerations</u>:

Subpart B(2) of Part 6132.2200 of the Minnesota Rules states, in part, that storage of reactive mine waste, at closure, must "permanently prevent substantially all water from moving through or over the mine waste." The proposed wet closure for the Flotation Tailings Basin, is designed to allow 6.5 inches per year of percolation (i.e., approximately one-fourth of the average annual precipitation rate) to pass through the tailings. In contrast, dry closure generally achieves much lower percolation rates into the waste, typically less than 5 percent of the average annual precipitation rate and often on the order of a few millimeters per year or less (e.g., see Wilson et al. 1995, Woyshner and Yanful 1995, Ayres et al. 2003, Keller et al. 2010). Although Permit Condition 45 requires the Permittee to continue exploring future closure options (including a dry cap), the DNR should consider making dry closure a permit condition rather than an option for PolyMet to explore at their discretion. Dry closure would be a much better approach for meeting the intent of Part 6132.2200 Subpart B(2).

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If you have any questions or concerns regarding these comments, please do not hesitate to contact me at 570-412-2069 or michael.malusis@bucknell.edu.

Sincerely,

Michael A. Malusis, Ph.D., P.E.
Consulting Engineer

AGU PUBLICATIONS

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RESEARCH ARTICLE
10.1002/2017JG003788

This article is a companion to Myrbo et al. (2017), https://doi.org/10.10022017JG003787 and Pollman et al. (2017), https://doi.org/10.10022017JG003785.

Key Points:
- Sulfate addition increased organic matter mineralization in wetland sediment, releasing C, N, P, and Hg to the water column
- Sulfate reduction caused not only higher methylmercury concentrations but higher total mercury concentrations in the surface water
- Increased sulfate loading to freshwaters can cause deleterious effects separate from direct sulfide toxicity to organisms

Supporting Information:
- Supporting Information S1
- Figure S1
- Data Set S1

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Increase in Nutrients, Mercury, and Methylmercury as a Consequence of Elevated Sulfate Reduction to Sulfide in Experimental Wetland Mesocosms

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Abstract Microbial sulfate reduction (MSR) in both freshwater and marine ecosystems is a pathway for the decomposition of sedimentary organic matter (OM) after oxygen has been consumed. In experimental freshwater wetland mesocosms, sulfate additions allowed MSR to mineralize OM that would not otherwise have been decomposed. The mineralization of OM by MSR increased surface water concentrations of ecologically important constituents of OM: dissolved inorganic carbon, dissolved organic carbon, phosphorus, nitrogen, total mercury, and methylmercury. Increases in surface water concentrations, except for methylmercury, were in proportion to cumulative sulfate reduction, which was estimated by sulfate loss from the surface water into the sediments. Stoichiometric analysis shows that the increases were less than would be predicted from ratios with carbon in sediment, indicating that there are processes that limit P, N, and Hg mobilization to, or retention in, surface water. The highest sulfate treatment produced high levels of sulfide that retarded the methylation of mercury but simultaneously mobilized sedimentary inorganic mercury into surface water. As a result, the proportion of mercury in the surface water as methylmercury peaked at intermediate pore water sulfide concentrations. The mesocosms have a relatively high ratio of wall and sediment surfaces to the volume of overlying water, perhaps enhancing the removal of nutrients and mercury to periphyton. The presence of wild rice decreased sediment sulfide concentrations by 30%, which was most likely a result of oxygen release from the wild rice roots. An additional consequence of the enhanced MSR was that sulfate additions produced phytotoxic levels of sulfide in sediment pore water.

Plain Language Summary In the water-saturated soils of wetlands, which are usually anoxic, decomposition of dead plants and other organic matter is greatly retarded by the absence of oxygen. However, the addition of sulfate can allow bacteria that respire sulfate, instead of oxygen, to decompose organic matter that would not otherwise decay. The accelerated decay has multiple consequences that are concerning. The bacteria that respire sulfate “breathe out” hydrogen sulfide (also called sulfide), analogous to the conversion or respiration of oxygen to CO_2. Sulfide is very reactive with metals, which makes it toxic at higher concentrations. In addition to the release of sulfide, the sulfate-accelerated decomposition of plants releases phosphorus and nitrogen, fertilizing the waterbody. Decomposition also mobilizes mercury (which is everywhere, thanks to atmospheric transport) into the surface water. The microbes that convert sulfate to sulfide also methylate mercury, producing methylmercury, the only form of mercury that contaminates fish. This study demonstrates that adding sulfate to a wetland can not only produce toxic levels of sulfide but also increase the surface water concentrations of nitrogen, phosphorus, mercury, and methylmercury.

1. Introduction

Organic matter (OM) accumulates in the sediments of aquatic systems when sediment concentrations of terminal electron acceptors (TEAs) are too low for microbes to completely decompose OM, especially when the supply of the most energy-efficient TEA, oxygen, is low. In water-saturated, organic-rich sediment, microbial sulfate reduction (MSR) can be a dominant pathway for the respiration of OM because oxygen is depleted in the uppermost sediment (Boye et al., 2017). Dissolved sulfate (SO_4) concentrations in continental surface

Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

waters are often low (less than 50 mgL^{-1} or 0.5 mmol L^{-1}) (e.g., Gorham et al., 1983) compared to ocean concentrations (2,800 mg L^{-1} or 29 mmol L^{-1}). Because of lower SO_4 concentrations, and because MSR rates can be limited by SO_4 concentrations (Holmer & Storkholm, 2001), the biogeochemical significance of MSR is often considered minimal in freshwater and low-salinity systems (e.g., Capone & Kiene, 1988; Nielsen et al., 2003; Stagg et al., 2017). However, absolute rates of MSR are not clearly lower in freshwater systems than in marine systems (Pallud & Van Cappellen, 2006), and in some cases, rapid cycling between oxidized and reduced forms of S can occur (Hansel et al., 2015).

In this study, we investigated the cascade of biogeochemical effects associated with increased MSR that result from increased surface water SO_4. We simultaneously quantified three different categories of biogeochemical responses related to MSR: (1) mineralization of organic matter and associated release of dissolved C, N, P, and Hg; (2) methylation of Hg; and (3) production of sulfide.

The stoichiometric release of the constituents of OM during MSR, notably C, N, and P, is a phenomenon long recognized by marine scientists. For instance, Boudreau and Westrich (1984) constructed a model of the MSR-mediated decomposition of marine sediment. They showed that SO_4 is reduced to sulfide (H_2S) in stoichiometric proportion to the mineralization of C, N, and P according to the reaction

$$2(CH_2O)_x(NH_3)_y(H_3PO_4)_z + xSO_4{}^{2-} \rightarrow 2xHCO_3{}^- + xH_2S + 2yNH_3 + 2zH_3PO_4 \tag{1}$$

C is released as both dissolved inorganic carbon (DIC, from complete oxidation, produced as bicarbonate alkalinity in stoichiometric proportion to sulfide (reaction (1); Boudreau & Westrich, 1984)) and dissolved organic carbon (DOC, from partial oxidation). The nutrients N and P are released in forms that are readily taken up by plants; N is released as ammonia, and P as phosphate. The mineralization of sediment organic matter associated with MSR releases sulfide (S^{2-}) into sediment pore water, which speciates, depending on the pH, into hydrogen sulfide (H_2S) and bisulfide (HS^-), henceforth collectively termed sulfide. If reduced S compounds accumulate in the sediment, there may be additional consequences to an aquatic system, such as toxic concentrations of sulfide in pore water (Lamers et al., 2013; Pastor et al., 2017; Myrbo et al., 2017) or conversion of sediment Fe(III) to FeS compounds, which enhances the mobilization of P (Curtis, 1989; Maynard et al., 2011).

The multiple biogeochemical consequences of MSR in freshwater systems have been investigated and documented in more than two dozen publications (Table S1 in the supporting information), which typically address a single issue, such as the production of alkalinity that neutralizes atmospherically deposited H_2SO_4 (Baker et al., 1986; Cook et al., 1986; and others) or the methylation of Hg (Gilmour et al., 1992; Branfireun et al., 1999, 2001; and others). Experimental studies addressing SO_4 reduction, sulfide production, associated OM mineralization, and release of nutrients have been broader (Lamers et al., 2001, 2002; Weston et al., 2006, 2011; and others), but aside from the results reported in this paper, only the experiments of Gilmour, Krabbenhoft, et al. (2007) and Gilmour, Orem, et al. (2007) have investigated all three categories of biogeochemical consequences of SO_4 reduction: OM mineralization, Hg methylation, and sulfide accumulation (Table S1). We also investigated the potential for Hg to be released by mineralization, a phenomenon proposed by Regnell and Hammar (2004).

Sulfate-driven enhanced mineralization of sediment OM and release of dissolved sulfide, N, P, DOC, DIC, and associated increases in alkalinity and pH have the potential to change the nature of an aquatic ecosystem. The immediate release is to the sediment pore water, but these dissolved materials can diffuse into the surface water. Increased internal loading of N and P can drive a system toward eutrophy, which can increase carbon fixation and amplify the cascade of biogeochemical effects associated with increased MSR. Increases in DOC also have the potential to fundamentally change the nature of a waterbody. DOC influences many processes in freshwater ecosystems, including light availability for macrophyte growth, thermal stratification, and bioavailability of metals, P, and C. In addition, DOC interferes with drinking water purification (Williamson et al., 1999). Increases in DIC, alkalinity, and pH can also change the nature of a system. Aquatic macrophyte and algal species often have different optimal alkalinity concentrations (e.g., Moyle, 1945; Vestergaard & Sand-Jensen, 2000), so increases in alkalinity may change aquatic community composition. Because pH is a master variable in aquatic systems (Stumm & Morgan, 2012), increases in pH can cause changes in both aquatic chemistry and the biota that dominate a system, as best documented by changes in diatom assemblages (Patrick et al., 1968).

Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

The release of sulfide into sediment pore water has multiple biological and geochemical consequences, several of which are related to the reactivity of sulfide with metals. If dissolved sulfide accumulates in pore water, it can negatively affect multicellular organisms inhabiting the sediment because sulfide can denature a range of metal-containing biomolecules, including cytochrome C oxidase, which is essential for respiration by both animals and plants (Bagarinao, 1992). Because aquatic sediment is a primary site of sulfide production, plants that root in sediment are vulnerable to toxic sulfide concentrations (Lamers et al., 2013; Pastor et al., 2017). However, if the watershed supplies sufficiently high loading of reactive Fe or other metals to the sediment, pore water sulfide concentrations may stay below toxic levels even while MSR proceeds as an important mineralization process (Pollman et al., 2017). The formation of FeS compounds effectively detoxifies sulfide (e.g., Marbà et al., 2007; Van der Welle et al., 2007). When Fe availability exceeds the production of sulfide, the accumulation of FeS is a measure of cumulative SO_4 reduction, which can be quantified as acid-volatile sulfide (AVS) (Heijs & van Gemerden, 2000). In addition, phosphorus is mobilized when oxidized Fe compounds with significant capacity to bind phosphate are converted to FeS compounds, which are incapable of binding phosphate (Lamers et al., 1998; Maynard et al., 2011). Thus, MSR mobilizes P both by mineralization of P-containing OM and by changing the form of Fe in sediment.

In addition to releasing C, N, and P, producing potentially toxic concentrations of sulfide, and reducing the solubility of metals, MSR is a primary process leading to the formation of MeHg, the bioaccumulative form of Hg (Gilmour et al., 1992; Hsu-Kim et al., 2013), although other microbial groups can also methylate Hg (Podar et al., 2015). In some cases, MSR can lead to toxic levels of MeHg higher in the food chain. The relationship between SO_4 concentrations and MeHg production is complex, however, and both field and laboratory studies in freshwater and saline ecosystems suggest that there is a dual effect of S on Hg methylation. At low SO_4 concentrations, the addition of SO_4 can stimulate MSR and Hg methylation (Jeremiason et al., 2006). At higher SO_4 concentrations, a greater abundance of inorganic sulfide appears to decrease the availability of inorganic Hg for Hg methylation (Hsu-Kim et al., 2013; Johnson et al., 2016). Because it has been observed that low SO_4 additions often increase Hg methylation and higher SO_4 concentrations decrease methylation, it has been proposed that there is a range of SO_4 and sulfide concentrations are optimal for Hg methylation, above which methylation is inhibited (Hsu-Kim et al., 2013). There is some debate regarding the underlying mechanism, but there is substantial evidence suggesting that dissolved inorganic sulfide above concentrations of 300–3,000 $\mu g\ L^{-1}$ has an inhibitory effect on Hg methylation (Bailey et al., 2017).

This study presents results from 30 wetland mesocosms in which the surface waters were treated to maintain a wide range of SO_4 concentrations over the course of 5 years (2011–2015) to assess the impact on wild rice, *Zizania palustris* (Pastor et al., 2017). We took advantage of this experiment to analyze the geochemical conditions in surface and pore water in the mesocosms during late summer 2013, 3 years into the experiment. Pastor et al. (2017) specifically examined the effect of increased SO_4 loading on wild rice, whereas this paper examines the broader biogeochemical impact of augmenting SO_4 to a low-SO_4 system.

2. Materials and Methods

2.1. Experimental Design

The experimental setup (Figure S1 in the supporting information), described in detail by Pastor et al. (2017), consisted of thirty 375 L polyethylene stock tanks containing sediment from a wild rice lake (Rice Portage Lake; +46.6987°, −92.6886°) in which wild rice was grown in self-perpetuating populations at five SO_4 treatment levels (control, 50, 100, 150, and 300 mg L^{-1}). SO_4 concentrations in six replicate mesocosms were routinely monitored, and amendments of SO_4 were added as Na_2SO_4 during the growing season as SO_4 was removed by MSR (Figure 1). Due to MSR, the mesocosm surface waters actually had time-weighted average concentrations of 7, 27, 59, 93, and 207 mg L^{-1}, respectively. Local well water containing an average of 10.6 mg L^{-1} SO_4 was added as needed to compensate for evapotranspiration. Precipitation in the region contains an average of 2.1 mg L^{-1} SO_4, and Rice Portage Lake has an average SO_4 concentration of 2.2 mg L^{-1} (Fond du Lac Band, 2016), so the control was slightly elevated above the ambient SO_4 concentration of the sediment source for the experiment. During the ice-free period (generally May through October), the surface water temperature (T) measured in the morning was correlated with the previous day's mean air temperature (mesocosm T = 0.72 air T + 4.4 °C; R^2 = 0.65). Peak air temperature is reached in July, when the average

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

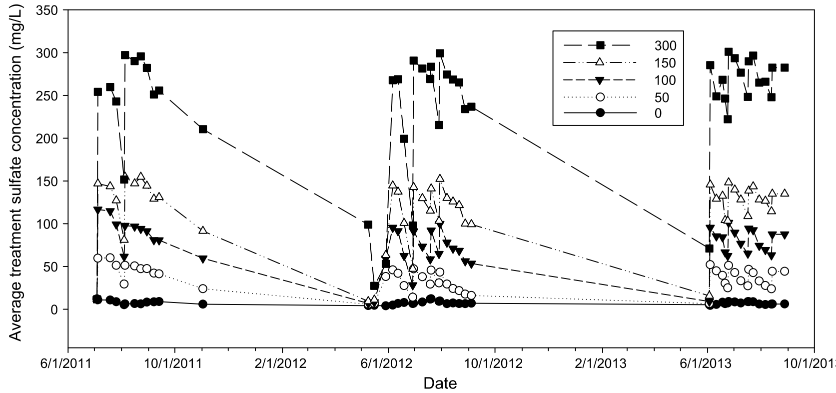

Figure 1. SO_4 concentrations in surface waters of each treatment, showing repetitive depletion and periodic amendment with Na_2SO_4 (average of six mesocosms per treatment on each sampling date).

temperature is 18.8°C (based on 1981–2010 air temperatures measured at the Duluth, Minnesota, airport, 10 km from the experimental site).

The experiments had been in progress for three growing seasons at the time of the sampling for this study, 27 and 28 August 2013, and for five growing seasons at the time of the second, less intensive, sampling (August 2015). The sediment of each mesocosm was divided into two parts for the 2013 growing season by a clear acrylic plate and all wild rice plants removed from one side in order to evaluate the effects of plant root presence on the geochemistry of the sediments. The plate was situated near one end of each mesocosm, such that about 10% of the surface area of 0.6 m^2 was plant-free (Figure S1). The plate was positioned to segregate the sediment without impeding the circulation of the surface water above all of the sediment. Sediment chemistry results presented here are from the side with wild rice plants present, except when analyzing the difference in AVS between the two sides.

2.2. Methods

2.2.1. Sample Collection

Rhizon™ samplers with a 10 cm long, 2.5 mm diameter, cylindrical porous tip (hydrophilic membrane pore size 0.12–0.18 μm (Rhizosphere.com, Netherlands; Shotbolt, 2010)), were connected by Teflon-taped Luer-Lok connectors and silicone tubing to a syringe needle. The sampler was inserted into the sediment, and the needle was then inserted through the 20 mm thick butyl rubber septum of an evacuated serum bottle (Bellco Glass) to initiate pore water draw through the tubing and displace air. After water was observed entering the serum bottle, the needle was removed from the first sacrificial bottle and inserted through the septum of a second evacuated serum bottle to collect the sample. One Rhizon and bottle were used to collect a sample for dissolved iron, preserved with 20% nitric acid. A second Rhizon and evacuated, N_2 gas-flushed sealed bottle, preloaded with 0.2 mL 2 N zinc acetate, 0.5 mL 15 M NaOH, and a stir bar, was used to collect a sample for dissolved sulfide analysis. Each Rhizon was positioned to sample pore water from the top 10 cm of sediment and to avoid collecting water from above the sediment surface. However, it is conceivable that some surface water was able to follow the path of the Rhizon into the sediment and dilute or partially oxidize the pore water sample.

Surface water in each mesocosm was collected for analysis of nitrate + nitrite, TP, TN, DOC, pH, temperature, and alkalinity from 5 cm below the surface of the water. Surface water samples for analysis of total Hg (THg) and MeHg were collected using clean hands/dirty hands protocols in September 2013, filtered through 0.45 μm glass fiber filters, and immediately acidified with 0.5% (by volume) trace metal hydrochloric acid. Samples were stored on ice during transport and at 4°C until analysis.

Pore water P availability was measured with three mixed bed ion exchange bags (Fisher Rexyn 300 resin) placed in the sediment of each tank in spring and harvested at the end of the growing season in 2013. A 3.8 cm diameter piston corer was used to obtain 10 cm long sediment samples for various analyses. Sediment samples for the analysis of AVS were taken monthly from June to October 2013 from replicate mesocosms of four SO_4 treatments (control, 50 150, and 300 mg L^{-1}; no mesocosm was sampled more

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

than once). Sediment samples were also taken on 8 October 2013 for the analysis of THg in bulk sediment and on 6 October 2015 for the analysis of total organic carbon (TOC).

2.2.2. Laboratory Analyses

Surface water and pore water analyses were conducted by the Minnesota Department of Health Environmental Laboratory (MDHEL). Total P was measured by in-line ultraviolet/persulfate digestion and flow injection (APHA, 2005, 4500 P-I), DOC by persulfate-ultraviolet oxidation and IR CO_2 detection (APHA, 2005, 5310-C), and alkalinity by automated titration (APHA, 2005, 2320-B). Pore water sulfide samples were prepared for inline distillation and flow injection colorimetric analysis using procedures that avoided exposure to oxygen. The sulfide serum bottle was weighed to determine the amount of sample collected and to adjust for the slight dilution factor of an alkaline antioxidant that was added by injection through the stoppers. The sealed samples were then placed on a stir plate for at least 1 h and subsamples withdrawn for analysis through a needle. Reanalysis of sealed, processed samples 12 months later shows no significant difference in sulfide concentrations, indicating that the sulfide samples were stable prior to analysis (data not shown). SO_4 concentration was measured using a Lachat QuikChem 8000 Autoanalyzer (Lachat Method 10-116-10-1-A). The resin was eluted using a KCl solution and analyzed for PO_4 using a Lachat Autoanalyzer, following the methods of Walker et al. (2006).

An aliquot of the nitrate + nitrite/TP/TN/DOC serum bottle was filtered in the lab within 10 days of sampling using a 0.45 μm filter, preserved to a pH $<$ 2 with 10% sulfuric acid, and transferred to a 250 mL polyethylene bottle for DOC analysis. The remaining sample was preserved to a pH $<$ 2, with 10% sulfuric acid and transferred to 250 mL polyethylene bottle for nitrate + nitrite/TP/TN analysis. The contents of the metal serum bottle were transferred to a 250 mL polyethylene bottle and preserved to a pH $<$ 2 with 10% nitric acid. Analyses were conducted within 30 days of sampling.

THg in surface water and bulk sediment were analyzed with EPA method 1631 by MDHEL, and surface water MeHg was analyzed with EPA method 1630 by Frontier Global Sciences (Bothell, Washington). Inorganic Hg (iHg) was calculated as the difference between THg and MeHg. Sediment AVS was analyzed colorimetrically, as above for pore water sulfide, following acid distillation and in-line alkaline trapping (APHA, 2005; SM 4500-S2). Sediment TOC was analyzed following SM5310C (APHA, 2005), using an OI Analytical Aurora 1030 at Pace Analytical Services, Virginia, Minnesota.

3. Data Analysis

3.1. Sulfate Depletion as the Independent Variable

Because SO_4 is relatively unreactive under oxidized conditions, its loss is attributable to diffusion or transpiration-driven advection (Bachand et al., 2014) into sediment and conversion to sulfide by bacteria. Surface water SO_4 concentrations decreased partly due to dilution by precipitation but largely from loss after movement into the sediment and reduction to sulfide. Sulfide would largely be retained in the sediment as FeS compounds, although some could be lost to the atmosphere as H_2S gas (Bagarinao, 1992) or as volatile organic sulfur compounds (Lomans et al., 2002). The cumulative SO_4 lost from surface water was calculated from a mass balance for each mesocosm from the inception of the experiment in spring 2011 through fall 2013; this quantity, termed here SO_4 depletion, $(SO_4)_{Depl}$, is used as a proxy for net MSR, following Weston et al. (2006). The surface water remained frozen from approximately 1 December to 1 April each winter, and the mesocosms were covered with plastic from November to late April each year and not amended with SO_4. SO_4 reduction was the major biogeochemical process altered by the experimental treatments, and therefore, $(SO_4)_{Depl}$ is the independent variable used in subsequent data analyses. It was only possible to perform a complete mass balance for SO_4, the only parameter consistently quantified in source water, precipitation, and overflow water.

3.2. Calculation of DIC From Measured Alkalinity

Dissolved inorganic carbon (DIC ≡ $[CO_3{}^{2-}] + [HCO_3{}^{-}] + [CO_2^*]$, where $[CO_2^*] = [CO_{2(g)}] + [H_2CO_3]$) was calculated from measured alkalinity and speciated using pH, temperature, and specific conductance of the surface water. At the pH range of the mesocosms (7.60–8.84), 95–98% of DIC is in the form of $HCO_3{}^{-}$, so DIC concentration on a molar basis is nearly the same as alkalinity (ALK) on an equivalent basis (DIC = 0.988 ALK + 0.077, $R^2 = 0.995$). In studies of freshwater, most inorganic carbon data are presented in terms of alkalinity because

Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

alkalinity is a familiar metric; however, in comparisons with DOC, inorganic carbon data are presented as DIC so that the units are directly comparable. PHREEQC version 3 geochemical modeling software (Parkhurst & Appelo, 2013) was used to calculate saturation indices for carbonate minerals.

3.3. Statistical Analysis

Statistical analysis was conducted with R version 3.2.3 and STATA (StataCorp, 2015). The effect of increased sulfate availability was assessed through both categorical analysis of the sulfate treatments (Kruskal-Wallis ANOVA test, followed by Dunn's test for multiple comparisons with Holm-Sidak corrections) and through linear regression and nonparametric Spearman rank correlations. We rely primarily on regressions against SO_4 depletion to detect the effects of enhanced sulfate-reduction driven mineralization, rather than categorical analysis of the sulfate treatment results, because (a) biogeochemical changes are not driven directly by SO_4 concentration, but rather by MSR, quantified as SO_4 depletion; (b) although SO_4 depletion may be highly correlated to SO_4 concentration, deviations between experimental mesocosms develop over time, so cumulative SO_4 depletion values eventually no longer align exactly with treatment categories, but rather become continuous variables; and (c) regression provides more statistical power than ANOVA and builds models that allowed us to describe the relationships between SO_4 depletion and response variables (Cottingham et al., 2005). However, when the relationship is not linear, ANOVA and comparison of treatments through Dunn's analysis can help describe the nature of a relationship.

4. Results and Discussion

4.1. The Impact of SO_4 Reduction on Mineralization of Sediment Organic Matter

Increased concentrations of surface water SO_4 resulted in increased sulfate reduction, which necessarily increased the mineralization of organic carbon, as described by reaction (1). Concentrations of surface water DOC and DIC increased in proportion to sulfate reduction, as measured by $(SO_4)_{Depl}$ (Table 1 and Figure 2). The marine literature generally assumes complete mineralization of particulate organic carbon (POC) to DIC in the water column (e.g., Boudreau & Westrich, 1984) (reaction 1), but in freshwater systems and especially wetlands, not all carbon is completely oxidized during decomposition, and a portion of POC may be mobilized as DOC (Howes et al., 1985; Selvendiran et al., 2008). In principle, the constituents of organic matter, such as the nutrients N and P, are mobilized in proportion to the mass of carbon mineralized as a result of MSR-driven decomposition. Surface water DOC and DIC, and the sum DOC + DIC, are therefore used as indicators of OM mineralization in interpreting the mobilization of N, P, and Hg to surface waters (Figure 2 and Tables 2 and 3).

In contrast to many marine systems, it is likely that SO_4 reduction in these sediments was limited more by SO_4 than by organic carbon, given that $(SO_4)_{Depl}$ was linearly proportional to the average SO_4 concentration (Figure S2a; R^2 = 0.87), without any obvious curvature to the relationship that would indicate saturation of MSR.

Regressions of surface water DOC and DIC against SO_4 depletion demonstrate that, on a net basis, about 60% more DIC than DOC was mobilized to the surface water as a result of MSR-driven mineralization (slope of 0.235 mM C per unit SO_4 depletion compared to 0.148; Table 2). The significantly positive slope of the DIC: DOC ratio against SO_4 depletion (Table 2) indicates that increasingly more DIC than DOC was observed in the surface water as sulfate depletion increased. Some mineralization of DOC to DIC likely occurs in the surface water as a result of exposure to oxygen, aerobic bacteria, and sunlight, processes that could have a larger effect as DOC increases.

Not only did surface water DIC and DOC increase in concert with sulfate reduction, but parallel increases occurred in surface water concentrations of constituents of organic matter: N, P, and Hg (Table 1 and Figure 2). DIC, DOC, total P, total N, ammonia, and total Hg in surface water all had increases from the control to the highest SO_4 addition of about twofold, (2.3, 1.7, 1.9, 1.8, 1.7, and 2.6-fold, respectively, Table 1). However, available phosphate in the sediment, an estimate of P availability in pore water, had a larger increase (7.5-fold). MSR consumes acidity as the DIC-based alkalinity is produced (Baker et al., 1986), which increased the average pH from 7.57 to 7.81, a 44% decrease in hydrogen ion concentration (Table 1). If the sulfide subsequently oxidizes (which could happen in a natural system during drought (Laudon et al., 2004) or intentional dewatering), a proportional quantity of alkalinity is consumed as acid is produced

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

Table 1
Summary of Effects of Experimentally Increased SO_4 Concentrations on SO_4 Reduction (Quantified as SO_4 Depletion), Organic Matter Mineralization, and Mercury Methylation

		Average of each sulfate treatment (*n* = 6 for each treatment)						Correlation with SO_4 depletion (Spearman)	
Variable	Matrix	Control	50	100	150	300	Max/Min	Rho	*p* value
		Variables mainly associated with SO_4 reduction							
SO_4 (T-W mean mg SO_4 L^{-1})	sw	6.7^a	26.9^{ab}	58.5^{abc}	93.2^{BC}	206.5^c	31.0	0.93	<0.0001
SO_4 depletion (mg S cm^{-2})	sw	0.14^a	2.52^{ab}	3.63^{abc}	4.28^{BC}	6.90^c	48.5	1	
Pore water sulfide (μg S L^{-1})	pw	69^a	184^a	224^a	393^b	728^b	10.5	0.81	<0.0001
Pore water iron (μg L^{-1})	pw	$12,883^a$	$11,122^{ab}$	$6,808^{abc}$	$4,483^{BC}$	$3,032^c$	4.25	−0.82	<0.0001
AVS (mg S kg^{-1})	sed	102^a	483^{ab}	NA	826^{ab}	$1,413^b$	13.8	0.77	<0.0001
pH	pw	7.57^a	7.52^a	7.55^a	7.75^a	7.81^a	1.03	0.39	=0.03
H^+ ion (μmol L^{-1})	pw	0.027	0.030	0.028	0.018	0.015	1.72	0.39	=0.03
		Variables mainly associated with mineralization of organic matter							
TOC (% dry mass)	sed	9.26^a	7.90^a	8.18^a	7.17^a	8.22^a	1.29	−0.34	=0.065
DIC (mg C L^{-1})	sw	28.9^a	47.2^{ab}	56.3^{BC}	56.7^{BC}	66.3^c	2.30	0.94	<0.0001
DOC (mg C L^{-1})	sw	16.3^a	21.4^a	26.8^{BC}	24.0^{abc}	28.3^{bc}	1.74	0.79	<0.0001
Total N (mg N L^{-1})	sw	1.42^a	1.75^a	2.35^{BC}	2.03^{abc}	2.57^{BC}	1.81	0.77	<0.0001
Ammonia (mg N L^{-1})	sw	0.09^a	0.09^a	0.10^a	0.10^a	0.16^a	1.70	0.38	=0.04
Total P (μg P L^{-1})	sw	13^a	16^{ab}	22^{ab}	21^{ab}	25^b	1.92	0.73	<0.0001
Available P (μg P g^{-1} resin)	Resin in sed	0.34^a	0.40^a	0.59^{ab}	0.92^{ab}	2.56^b	7.45	0.86	<0.0001
Total Hg (ng L^{-1})	sw	1.83^a	2.09^a	3.61^{ab}	3.25^{ab}	4.80^b	2.63	0.82	<0.0001
		Variables mainly associated with Hg methylation							
Methylmercury (ng Hg L^{-1})	sw	0.20^a	0.49^{ab}	1.21^b	1.08^b	1.18^b	5.91	0.66	<0.0001
Inorganic Hg (ng L^{-1})	sw	1.63^a	1.60^{ab}	2.40^{abc}	2.17^{BC}	3.62^c	2.22	0.80	<0.0001
Percent methylmercury	sw	$11\%^a$	$23\%^{ab}$	$30\%^b$	$32\%^b$	$23\%^{ab}$	2.90	0.45	=0.02

Note. Matrix abbreviations: sw = surface water, pw = pore water, sed = bulk sediment. Averages with superscript letters in common are not significantly different at the 0.05 level.

(Hall et al., 2006). However, the sulfide reoxidation does not reverse the mobilization of the constituents of organic matter (C, N, P, and Hg) or the production of methylmercury (MeHg; see below). Rather, any production of SO_4 from sulfide oxidation creates the potential for additional MSR-driven OM mineralization and Hg methylation (Coleman Wasik et al., 2015; Hansel et al., 2015).

The slope of linear regressions of the C, N, and P in surface water against $(SO_4)_{Depl}$ is an estimate of the increase of that variable in mesocosm surface waters per unit SO_4 reduction (Table 2). The regression slopes provide a basis for estimates of stoichiometric ratios of the constituents mobilized from the sediment solid phase, similar to the calculation that Weston et al. (2006) performed for pore water. The calculation of stoichiometric ratios from the slopes of regressions with $(SO_4)_{Depl}$ is more accurate than calculating ratios from surface water concentrations alone, as the use of slopes accounts for the concentrations of the control (the intercept of the linear regression).

The regression slopes of surface water C versus surface water N, P, and Hg in mesocosms are estimates of the net release of each element relative to that of C (Table 3). These estimates can then be compared to the ratio of these constituents in the primary source material—the sediment—to determine the efficiency of mobilization of sediment N, P, and Hg to surface water, compared to C (Table 3). Although we present efficiency relative to only DOC and only DIC, calculating efficiency relative to the sum of mineralized OM (DOC + DIC) represents the overall net efficiency of mineralization, which ranges from 8% to 38% for the three constituents (Table 3). Although the increases in surface water N, P, and Hg are consistent with the hypothesis that those elements were released to the surface water through sulfate-enhanced mineralization of sediment OM, their lower mobilization efficiencies relative to carbon suggest that other processes were operating to either increase carbon, decrease N, P, and Hg mobilization relative to carbon, and/or increase N, P, and Hg losses. It is likely that some carbon was introduced to the surface waters from sources other than the sediment (e.g., photosynthetic fixation of atmospheric carbon) and that there were losses for N, P, and Hg from the surface water (though adsorption, settling, biological uptake, or atmospheric evasion of N and Hg).

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

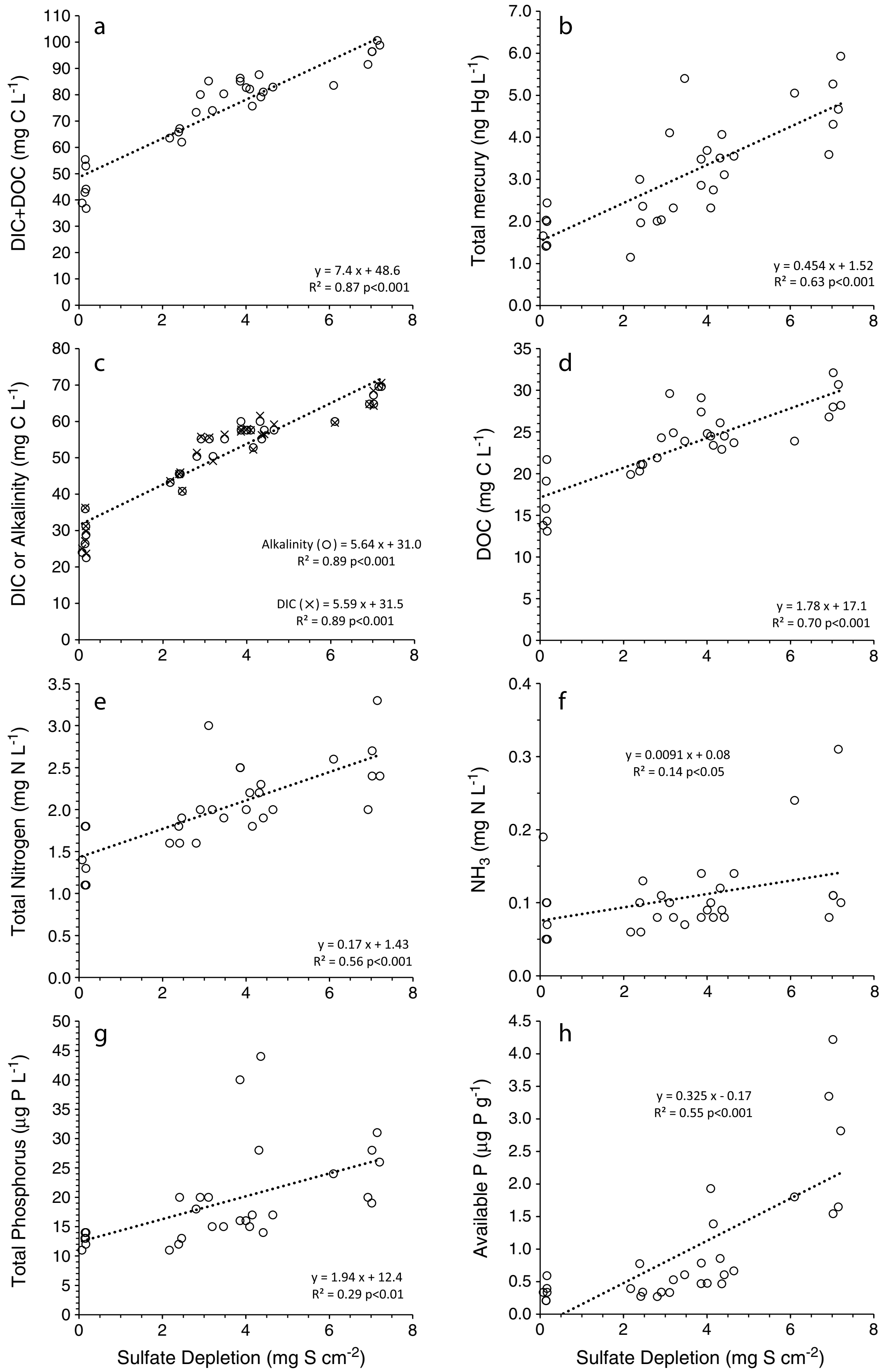

Figure 2. The release of constituents of sedimentary organic matter as a function of SO_4 depletion, showing linear regressions (dotted lines). (a) Sum of surface water DIC and DOC; (b) surface water total mercury; (c) surface water alkalinity and DIC (symbols ○ and ×, respectively; the two regressions are superimposed); (d) surface water DOC; (e) surface water total nitrogen; (f) surface water ammonia; (g) surface water total phosphorus; (h) available phosphate in the sediment, as quantified on ion-exchange resin.

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

Table 2
Slopes of Regressions of Surface Water Parameters (mM) Against SO_4 Depletion (mg S cm^{-2})

Surface water variable (molar basis)	Regression against $(SO_4)_{Depl}$ (mg S cm^{-2}) Slope	R^2	p
DIC	0.235	0.89	<0.0001
DOC	0.148	0.70	<0.0001
DIC + DOC	0.383	0.84	<0.0001
DIC: DOC	0.044	0.56	<0.0001
TN	0.0121	0.56	<0.0001
TN: DIC	−0.0028	0.25	<0.01
TN: DOC	0.0004	0.01	NS
TN: DIC + DOC	−0.0006	0.08	NS
TP	6.26E–05	0.29	<0.002
TP: DIC	−7.00E–06	0.03	NS
TP: DOC	7.00E–06	0.02	NS
TP: DIC + DOC	−1.00E–07	0.00	NS
THg	2.26E–09	0.63	<0.0001
THg: DIC	9.00E–06	0.46	<0.0001
THg: DOC	6.00E–06	0.23	<0.01
THg: DIC + DOC	2.00E–05	0.42	<0.0001

Note. When a sediment constituent's ratio to DIC or DOC has a significant slope against sulfate depletion, it indicates that the constituent was mobilized to the surface water at a significantly different rate than the DIC or DOC.

In addition to increases of TP in the surface water, the sediment pore water in the highest SO_4 treatment contained 7.5-fold greater available phosphate than the controls, as quantified with ion-exchange resin (Table 1 and Figure 2h). In comparison, the increase in surface water TP was only 1.9-fold (Table 1 and Figure 2g). The difference between phosphorus response in the resin and the surface water may be partly due to (a) loss of TP from the surface water after mobilization or (b) irreversible trapping of mobilized P on the resin. If phosphorus is released from sediment en masse in response to an S-induced shift from iron oxides to iron sulfides, the sediment pore water would experience this release first, while release to surface waters would take longer due to diffusion-limited transport and potentially an iron-oxide barrier at the sediment-water (anoxic-oxic) interface.

DIC in surface water is not conservative, being subject to exchange across the air-water interface, carbonate mineral precipitation, and photosynthetic uptake. Surface water pCO_2 in all mesocosms was above saturation with respect to atmospheric equilibrium by a factor of 1.4–15.5 (based on the DIC speciation calculations discussed earlier; data not shown), so the mesocosms were losing, not gaining, C through gas exchange with the atmosphere. The pCO_2 values in the mesocosms are similar to those reported from epilimnia of small, organic-rich, temperate lakes of low to moderate salinity (Cole et al., 1994; Myrbo & Shapley, 2006). With respect to mineral precipitation, based on geochemical equilibrium calculations, surface waters were undersaturated with respect to all carbonate minerals. Thus, although DIC in surface water is subject to several transport and transformation processes, the sustained presence of CO_2 at quantities significantly above saturation with respect to the atmosphere and the observation of increasing DIC and DOC with increasing $(SO_4)_{Depl}$ (Table 1) provide strong evidence of sulfate-induced increases in net carbon mineralization in the mesocosms.

In addition to the carbon originally present in the sediment, organic carbon was also photosynthetically fixed by wild rice and algae in the mesocosms and subsequently subjected to respiration and some decomposition, adding to the DIC and DOC in surface waters. DOC may also have been released into sediment pore water as an exudate from the wild rice roots (Rothenberg et al., 2014; Windham-Myers et al., 2009). Exudate DOC, however, does not account for the observed increase in DOC, since a negative relationship between the number of wild rice plants and DOC was observed (Spearman's rho = -0.63, $p < 0.001$, Table S2).

4.2. Effects of SO_4 Reduction on Mercury and Methylmercury in Surface Water

We interpret Hg mobilization to the surface water in an analogous manner to C, N, and P, as Hg tends to associate strongly with organic matter in sediment (Feyte et al., 2010). In the mesocosm surface waters,

Table 3
Elemental Ratios in Sediment and Surface Water Across the Range of SO_4 Depletion

Molar ratio in sediment[a]		Molar ratio in surface water[b] DIC	DOC	DOC + DIC	Efficiency of mobilization of sediment N, P, or Hg to surface water, relative to carbon DIC	DOC	DOC + DIC
C: N	12[a]	19	12	32	63%	100%	38%
C: P	463[a]	3,752	2,366	6,118	12%	20%	8%
C: Hg	1.90E + 07	1.04E + 08	6.5E + 07	1.69E + 08	18%	29%	11%

Note. Together, the ratios are used to calculate the efficiency of mobilization of the constituents of particulate organic matter into the surface water.
[a]Sediment data from Hildebrandt, Pastor, and Dewey (2012), a mesocosm study that obtained sediment from the same natural wild rice stand. [b]Regression slopes of C versus N, P, and Hg in mesocosm surface waters; calculations are made based on surface water DIC alone, surface water DOC alone, and the sum of surface water DOC + DIC.

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

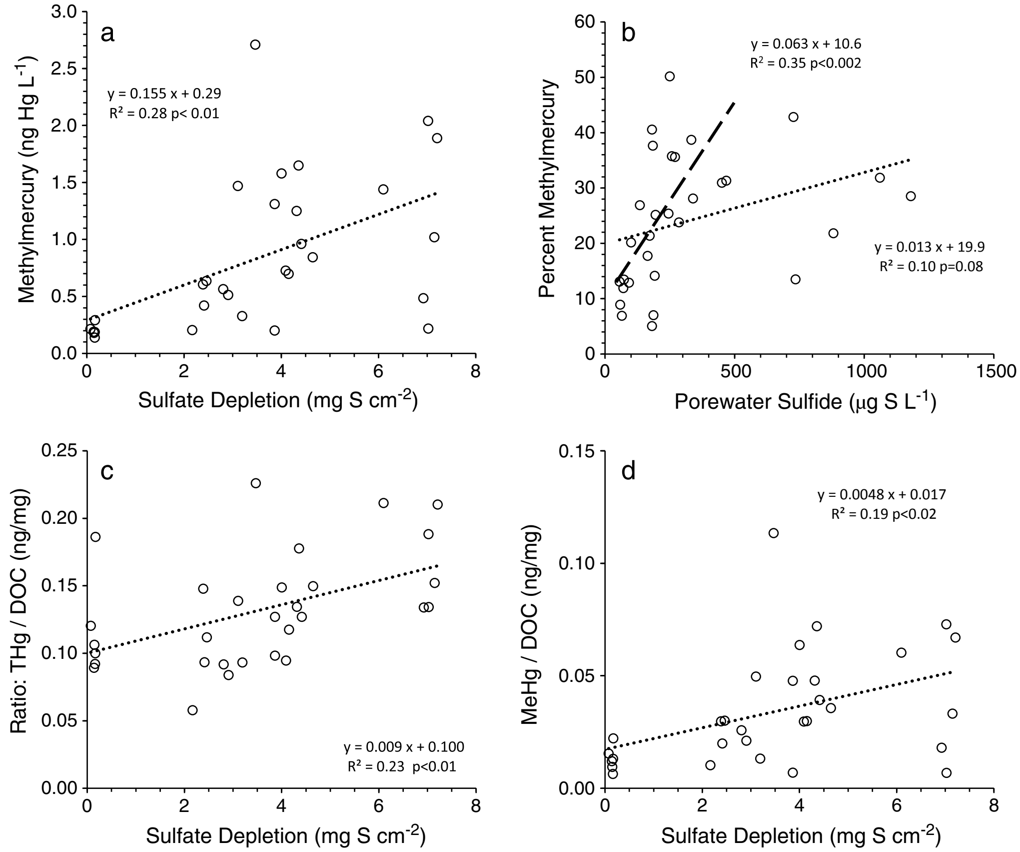

Figure 3. The response of surface water Hg variables to SO_4 depletion and the production of pore water sulfide, showing linear regressions. (a) MeHg as a function of SO_4 depletion; (b) percent MeHg as a function of pore water sulfide, showing regressions for all data (dotted line) and for the subset of data extending only to a pore water sulfide concentration of 468 μg S L^{-1} (dashed line); (c) ratio of THg to DOC as a function of SO_4 depletion; (d) ratio of MeHg to DOC as a function of SO_4 depletion.

THg, inorganic Hg (iHg), and MeHg all increased significantly with increased $(SO_4)_{Depl}$ (Table 1 and Figures 2b and 3a, $p < 0.0001$) and were greater in the highest sulfate amendment by factors of 2.6, 2.2, and 5.9, respectively (Table 1). The relative increase in THg (2.6-fold) is greater than that for DIC, DOC, TN, and TP, which range from 1.7 to 2.3-fold (Table 1). DOC enhances the solubility of both iHg and MeHg and can facilitate the movement of Hg from sediment into surface water (Ravichandran, 2004). The 5.9-fold increase in MeHg indicates that MeHg flux to surface waters was enhanced by sulfate loading disproportionately more than sedimentary release of THg (2.6-fold) and the increase in surface water DOC (1.7-fold).

The genes required to methylate Hg have been found in a wide variety of anaerobic bacteria, including SO_4-reducing bacteria, iron-reducing bacteria, and methanogens (Podar et al., 2015). Though some pure culture and experimental evidence exist for mercury methylation by other bacteria, extensive pure culture, experimental, and landscape-scale observations suggest SO_4-reducing bacteria dominate Hg methylation in many freshwater and marine environments. The relatively large increase in surface water MeHg in response to increased $(SO_4)_{Depl}$ in this experiment supports the assumption that MSR was responsible for most of the observed production of MeHg. It is likely that increased SO_4 loading to low-SO_4 aquatic systems with organic sediment will result in increased Hg methylation even though the relative importance of Hg methylation in the environment by different groups of bacteria is still a subject of debate (Paranjape & Hall, 2017).

If movement of DOC from sediment to surface water were the sole mechanism for the Hg increase in surface water, a constant Hg:DOC ratio would be expected on the $(SO_4)_{Depl}$ gradient. However, THg:DOC, iHg:DOC, and MeHg:DOC ratios in surface water are all significantly correlated with SO_4 depletion (Table S2 and Figures 3c and 3d). Therefore, all forms of Hg (THg, iHg, and MeHg) increase in surface waters more than

Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

does DOC, indicating that a sulfate-induced enhancement of carbon mineralization may act in combination with either enhanced methylation or an enhanced capacity of DOC to carry Hg. Changes to the binding strength of the DOC in heavily S-impacted mesocosm sediment are possible, as thiol groups on DOC are dominant binding sites for Hg (Skyllberg, 2008). The dual role of organic carbon and sulfur in driving both the production of MeHg and the transport of MeHg could be responsible for the substantially larger maximum increase in MeHg:DOC ratio relative to the increase in the THg:DOC ratio (an average 206% increase relative to a 63% increase, Figures 3c and 3d), as postulated by Bailey et al. (2017).

Regnell and Hammar (2004) identified three MSR-driven processes that might cause mobilization of Hg from sediment in a wetland, (1) mineralization of organic matter; (2) extraction of iHg by reduced S compounds, which could be associated with mobilized DOC; and (3) enhanced production of MeHg, which is more mobile than iHg. They argued that enhanced production of MeHg explained THg mobilization in the minerotrophic peat bog that they studied. However, in this study, increases in surface water MeHg concentrations (Figure 3a) are not sufficient to explain the linear increase in THg observed in this experiment (Figure 2b) because most (67%) of the increase is iHg (Table 1). Some of the increase in surface water iHg could be the result of increased production of MeHg that moved to surface water and was subsequently demethylated. Regardless of the underlying mechanism, our observations clearly show increases in surface water Hg that were greater than the increases in C, N, and P (Table 3); this corroborates other studies (Bouchet et al., 2013; Merritt & Amirbahman, 2007; Regnell & Hammar, 2004) that suggest sediment Hg may be synergistically mobilized to surface waters through mineralization, methylation, and enhanced mobility with DOC.

Recent research has shown that in many ecosystems, higher concentrations of pore water sulfide may inhibit MeHg production through either thermodynamically or kinetically controlled reactions with inorganic Hg (Benoit et al., 2003; Hsu-Kim et al., 2013). We plotted %MeHg, rather than the MeHg concentration, against pore water sulfide because we are interested in identifying the pore water sulfide zone of greatest efficiency for the methylation and mobilization of mercury. In this experiment the MSR-driven mineralization of OM released THg to surface water in addition to producing pore water sulfide. Accordingly, because THg is not constant, plotting %MeHg is the most accurate way to identify peak methylation efficiency. In principle, the restricted bioavailability of Hg to methylating bacteria results in a maximum in MeHg production at intermediate concentrations of pore water sulfide. Consistent with previous research in sulfate-impacted freshwater ecosystems (Gilmour et al., 1998; Gilmour, Krabbenhoft, et al., 2007, Gilmour, Orem, et al., 2007; Bailey et al., 2017), MeHg production was most efficient at intermediate sulfide concentrations. In the control, where average sulfide was 69 μg S L^{-1}, MeHg averaged only 11% of THg in surface waters. In the intermediate SO_4 treatments, which had average sulfide concentrations of 224 and 393 μg S L^{-1}, MeHg production efficiency peaked significantly higher, at averages of 30% and 32%, respectively (Table 1). %MeHg declined to an average of 23% in the highest SO4 treatment, which had an average sulfide concentration of 728 μg S L^{-1}. Given the relatively great scatter in the relationship between %MeHg and sulfide (Figure 3b), it would be most defensible to conclude that the decrease in %MeHg began to occur somewhere between 300 and 700 μg S L^{-1}. There is a strong positive relationship ($p < 0.001$) between sulfide and %MeHg if the five sulfide concentrations greater than 727 μg S L^{-1} are excluded from the regression (which leaves only sulfide concentrations less than 468 μg S L^{-1}, since there is a gap in sulfide concentrations; Figure 3b). Other studies have identified sulfide zones of peak methylation roughly comparable to that found here. In South Florida, Orem et al. (2011) found that sulfide ranging from 5 to 150 μg S L^{-1} did not inhibit methylation but that sulfide concentrations greater than 1,000 μg S L^{-1} did. In a subboreal Minnesota wetland enriched in SO_4 from mining discharge, Bailey et al. (2017) found that sulfide concentrations above ~650 μg S L^{-1} inhibited methylation.

The relationship between surface water SO_4 and Hg methylation can be strongly affected by site-specific conditions. Because of the variable conversion of SO_4 in surface water to sulfide in pore water—primarily due to differences in OM and Fe availability (Pollman et al., 2017)—researchers have found a broad range in the SO_4 concentration associated with maximum efficiency of Hg methylation. For example, Orem et al. (2014) observed that two different areas in the Everglades Protection Area had peak surface water MeHg concentrations at SO_4 concentrations of 2 and 10–15 mg L^{-1}. In the mesocosms presented here peak surface water %MeHg was observed in the two sulfate treatments that averaged 59 and 93 mg L^{-1} (Table 1).

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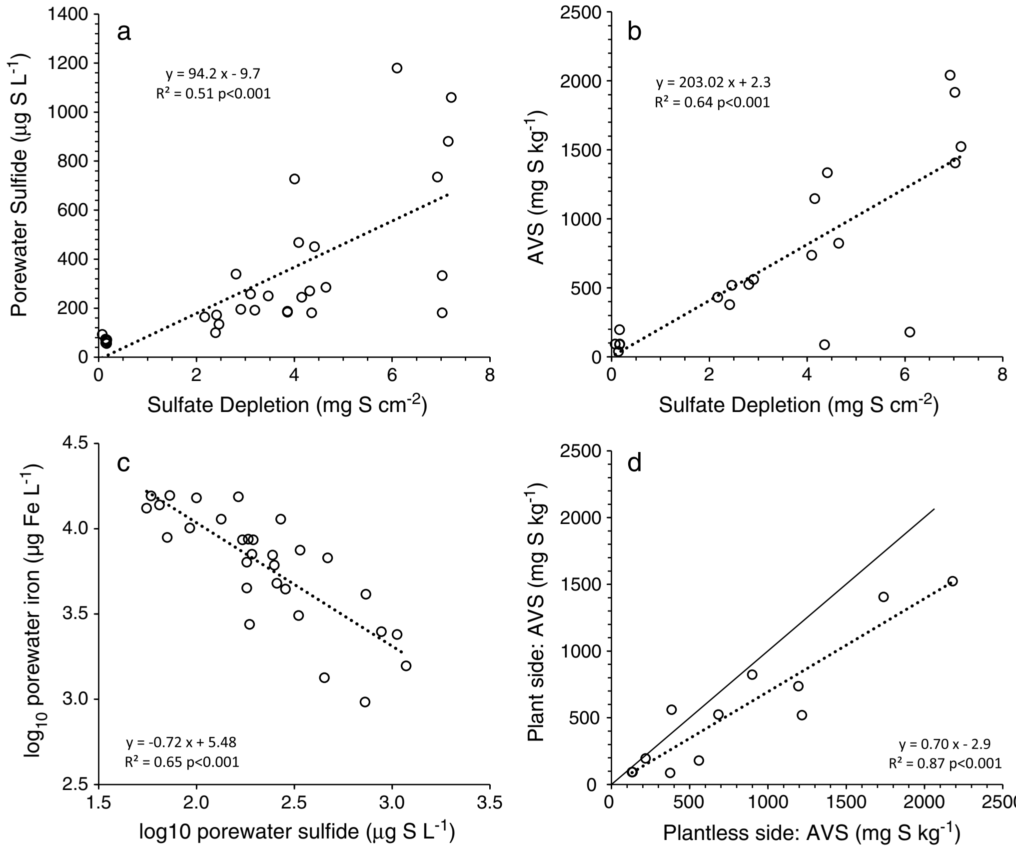

Figure 4. AVS and pore water sulfide, as related to SO_4 depletion, pore water iron, and presence of rooted plants. (a) Pore water sulfide as a function of SO_4 depletion; (b) AVS from the vegetated side of the mesocosms as a function of SO_4 depletion; (c) pore water iron as a function of pore water sulfide; (d) AVS compared between the vegetated side and nonvegetated side. The solid 1:1 line shows that in almost all mesocosms more AVS is found in the side without plants.

4.3. Effects of SO_4 Reduction on Pore Water and Sediment Sulfide

Pore water sulfide increased at higher $(SO_4)_{Depl}$, although with greater variance at higher $(SO_4)_{Depl}$ (Figure 4a), possibly as a result of variable oxidation of sulfide that may depend on the proximity of the Rhizon sampler to plant roots (Schmidt et al., 2011) or of variable bioturbation by invertebrates (Lawrence et al., 1982). When SO_4 is reduced through MSR, the sulfide produced has a number of nonexclusive potential fates: the sulfide could (1) be oxidized within the sediment; (2) remain in the sediment pore water as free sulfide; (3) diffuse into oxygenated surface water, to be oxidized; (4) react with metals in the sediment, forming insoluble precipitates (dominated by iron-sulfide compounds); or (5) be lost to the atmosphere as H_2S gas or as volatile organic sulfur compounds. Because precipitation reactions are fast relative to redox reactions and diffusion, most of the sulfide probably forms metal precipitates if metals are available. When precipitation dominates the fate of sulfide produced from MSR, the continuous reduction of SO_4 and precipitation of iron sulfides form quasi-steady states between surface water SO_4 and pore water sulfide (Figure S2b) and between pore water sulfide and pore water iron (Figures 3 and 4c). The overall mass of sulfide in the mesocosm sediment, quantified through analysis of AVS (from sediment in the vegetated area), is closely correlated with SO_4 depletion (Figure 4b) even though AVS may not include all the reduced sulfide in sediments. It is likely that most of the AVS in these sediments is present as an FeS precipitate because other metals are at low concentrations in these sediments, which came from a relatively pristine (unpolluted) lake (Fond du Lac Band, 2016; Pastor et al., 2017). Note that there are two mesocosms with especially low AVS concentrations (Figure 4b). It is possible that the AVS in the specific location in these mesocosms where sediment core samples were collected was influenced by

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a spatially heterogeneous oxidization process (e.g., root oxygen or benthic invertebrates) that limited the accumulation of sulfide.

AVS was 30% lower in the vegetated side of the mesocosms, suggesting that wild rice released oxygen into the sediment, inhibiting the production of sulfide and/or decreasing sulfide concentrations through oxidation (Figure 4d; Wilcoxon paired test, $p = 0.007$). It is notable that this 30% difference developed in just one growing season, despite the previous 2 years of sulfate treatment. Pore water sulfide showed no statistically significant difference between the two sides owing to high variability within treatments. Numerous investigations have found that rooted aquatic plants release oxygen from their roots, a phenomenon that is usually interpreted as an adaptation to limit the toxicity of reduced chemical species in the pore water, especially sulfide (Lamers et al., 2013). Although oxygen release has been observed in white rice, *Oryza sativa* (Colmer, 2002), it has never been documented in wild rice, which is in the same tribe (Oryzeae) of grasses as white rice, and also develops aerenchyma (Jorgenson et al., 2013), plant structures that provide a low-resistance internal pathway for movement of oxygen to the roots. Since the growth and reproduction of rooted plants can be inhibited by sulfide (Pastor et al., 2017), there may be a tipping point of exposure to sulfide above which oxygen release is insufficient to mitigate phytotoxic effects, and the plant population declines over time, possibly to extirpation. In this experiment, in the third treatment year, the increase in pore water sulfide was the apparent cause of a decrease in the average number of wild rice stems from 17 in the control mesocosms to 3 in the highest-sulfate treatment mesocosms (Pastor et al., 2017).

4.4. Mesocosms as Models for Ecosystem-Scale Effects of SO_4 Reduction

Although mesocosms, as contained ecosystems, are useful because they mimic ecological and biogeochemical processes that occur in the field, extrapolating findings to nature is challenging when plastic walls have prevented exchange of water and materials (Petersen et al., 2009). These wall-based challenges are manifest in three phenomena in this experiment, (1) relatively long surface water residence times due to the lack of a constant throughflow; (2) the presence of the wall itself, which provides a surface for periphyton; and (3) lack of either overland or groundwater loading of external materials:

1. Relatively long surface water residence times: the increased loading of N, P, C, Hg, and MeHg to the surface water of the mesocosms was readily detected because the lack of hydraulic loading from a watershed minimized dilution and loss through the outflow. The impact of an increase in SO_4 loading on surface water concentrations of N, P, C, Hg, DIC, and DOC would be lower in waters with shorter residence times. For instance, Baker and Brezonik (1988), in modeling increases in alkalinity from atmospheric SO_4 loading, noted that net increases in alkalinity would be most important in waters with long residence times ($>$5 years) and that there would be little increase in alkalinity in waters with much shorter residence times ($<$1 year). However, the measured concentrations may not represent the maximum impact of MSR-driven mineralization because the mesocosm wall may enhance removal from the surface water (point number 2, below).
2. Presence of the mesocosm wall: the mesocosms have a relatively high ratio of wall and sediment surfaces to the volume of overlying water, enhancing the removal of surface water nutrients and Hg to periphyton or inorganic sinks such as iron oxyhydroxides. Natural aquatic systems have less proportional loss to surfaces. The quantitative estimates of internal loading of N, P, and Hg in response to MSR-induced carbon mineralization may have been underestimated by the measured surface water concentrations, given that significant loss of these constituents to periphyton may have occurred. In addition, THg was filtered prior to analysis, which would have removed any Hg associated with phytoplankton or other suspended particles.
3. Lack of either overland or groundwater loading of particulate and dissolved material, specifically iron: the availability of iron in sediment is a primary controller of the fate of MSR-produced sulfide (Pollman et al., 2017). In natural aquatic systems, iron would be supplied at a relatively constant rate from the system's watershed over the long term, although varying in magnitude from watershed to watershed (Maranger et al., 2006; Winter, 2001). This experiment was not an accurate long-term mimic of pore water sulfide concentrations because the external supply of iron was cut off at the inception of the experiment. With no loading of iron, but continued loading of SO_4, the continued production of sulfide would be expected to eventually consume all available Fe, allowing pore water sulfide levels to exceed those expected in a natural system at equivalent surface water SO_4 concentrations. This mesocosm experiment provides

AGU Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003788

evidence for just such a result. The experiment continued for 2 years after the 2013 sampling presented here. In the fifth year (August 2015) pore water sulfide was much greater than had been observed in 2013, and disproportionately so in the highest SO_4 treatment, which was most likely to consume available Fe. Between the 2013 and 2015, pore water sulfide increased in the control SO_4 treatment (about 7 mg SO_4 L^{-1}) from an average value of 69 μg L^{-1} in 2013 to 116 μg L^{-1} in 2015, a 68% increase. Pore water sulfide in the highest treatment (nominally 300 mg SO_4 L^{-1}, Table 1) increased from an average value of 728 μg L^{-1}in 2013 to 9,350 μg L^{-1} in 2015, a 1,184% increase (Pastor et al., 2017). In a survey of 108 Minnesota waterbodies with a wide range of surface water sulfate, only two exceeded a pore water sulfide level of 3,200 μg L^{-1} (Myrbo et al., 2017).

5. Conclusions

This study demonstrates that increased SO_4 loading to inland waters with organic-rich sediments can significantly increase the decomposition of sedimentary organic matter, which increases internal loading to surface water of the chemical constituents of organic matter, including DIC, DOC, P, N, and Hg. Associated changes include increased production of sulfide and methylmercury and increased alkalinity and pH. Any one of these changes could alone cause significant secondary changes in the structure of an aquatic ecosystem but, taken together, could cause a cascade of primary and secondary environmental changes: increased availability of nutrients (N and P), which can alter dominant plant species, organic carbon production, oxygen consumption, and redox; increased pore water sulfide, which can be toxic to benthic animals and plants; increased MeHg production, which can affect fish and other consumers in the aquatic food web; increased DOC, which can alter light transmission, thermal stratification, and aquatic chemistry; and increased DIC production, which increases alkalinity and pH, affecting aquatic chemistry and biota. Each of these changes resulting from higher surface water SO_4 and consequent increases in MSR has been documented in the literature, but the entire suite of associated changes in aquatic chemistry has not heretofore been demonstrated in an integrated fashion. The degree to which an increase in SO_4 loading affects the ecological structure of the receiving water will depend on the relative increases in N, P, DIC, DOC, Hg, MeHg, pH, and sulfide, which will be a function of background geochemistry and hydrology of the specific system. In this experiment, the changes in these parameters were linearly proportional to SO_4 reduction, which, in turn, was linearly proportional to the time-weighted average SO_4 concentration. The linear responses of the parameters to SO_4 additions suggest that ecologically significant changes may occur even when SO_4 concentrations are elevated only modestly and that dramatic changes may occur with higher sulfate loading.

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Prepared in cooperation with the Federal Emergency Management Agency

Floods of June 2012 in Northeastern Minnesota

Scientific Investigations Report 2012–5283

U.S. Department of the Interior
U.S. Geological Survey

Cover. Left: View of homes flooded by the St. Louis River in the Fond du Lac neighborhood of Duluth, Minnesota, taken from a helicopter on June 21, 2012 (photograph provided by Walter Leu, Minnesota Department of Transportation).
Top right: An inundation map showing approximate flood-peak extents and depths for June 2012 for the St. Louis River at the Fond du Lac neighborhood of Duluth, Minnesota (entire map is in appendix 2 of the report). Map prepared by Christiana Czuba, U.S. Geological Survey, November 2012. Map base from 2010 National Agricultural Imagery program (U.S. Department of Agriculture, 2010).

Floods of June 2012 in Northeastern Minnesota

By Christiana R. Czuba, James D. Fallon, and Erich W. Kessler

Prepared in cooperation with the Federal Emergency Management Agency

Scientific Investigations Report 2012–5283

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Contents

Figures

Tables

Appendix 1

Appendix 2

Appendix 3

Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0.0254	meter per hour (m/h)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) or the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Water year is the 12-month period of October 1 through September 30 designated by the calendar year in which it ends.

Abbreviations

AEP	annual exceedance probability
CDT	Central Daylight Time
CSG	crest-stage gage
DEM	digital elevation model
FEMA	Federal Emergency Management Agency
GIS	geographic information system
GPS	global positioning system
LiDAR	light detection and ranging
MDNR	Minnesota Department of Natural Resources
MDPS	Minnesota Department of Public Safety
MHSEM	Minnesota Homeland Security and Emergency Management
MnDOT	Minnesota Department of Transportation
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RTK–GPS	Real-Time Kinematic Global Positioning System
TIN	triangular irregular network
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WIE	weighting of independent estimates

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U.S. Geological Survey staff who were instrumental in flood documentation for this study include Dan Daly, Erik Lahti, Greg Mitton, Brett Savage, Russ Buesing, Jeff Copa, John Greene, Josh Larson, Ben Otto, Eric Wakeman, John Kent, and Kristen Kieta. Chris Ellison and Moon Kim are thanked for critical reviews of this report.

Floods of June 2012 in Northeastern Minnesota

By Christiana R. Czuba, James D. Fallon, and Erich W. Kessler

Abstract

During June 19–20, 2012, heavy rainfall, as much as 10 inches locally reported, caused severe flooding across northeastern Minnesota. The floods were exacerbated by wet antecedent conditions from a relatively rainy spring, with May 2012 as one of the wettest Mays on record in Duluth. The June 19–20, 2012, rainfall event set new records in Duluth, including greatest 2-day precipitation with 7.25 inches of rain. The heavy rains fell on three major watersheds: the Mississippi Headwaters; the St. Croix, which drains to the Mississippi River; and Western Lake Superior, which includes the St. Louis River and other tributaries to Lake Superior. Widespread flash and river flooding that resulted from the heavy rainfall caused evacuations of residents, and damages to residences, businesses, and infrastructure. In all, nine counties in northeastern Minnesota were declared Federal disaster areas as a result of the flooding.

Peak-of-record streamflows were recorded at 13 U.S. Geological Survey streamgages as a result of the heavy rainfall. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities were tabulated for 35 U.S. Geological Survey streamgages. Flood-peak streamflows in June 2012 had annual exceedance probabilities estimated to be less than 0.002 (0.2 percent; recurrence interval greater than 500 years) for five streamgages, and between 0.002 and 0.01 (1 percent; recurrence interval greater than 100 years) for four streamgages. High-water marks were identified and tabulated for the most severely affected communities of Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River). Flood-peak inundation maps and water-surface profiles were produced for these six severely affected communities. The inundation maps were constructed in a geographic information system by combining high-water-mark data with high-resolution digital elevation model data. The flood maps and profiles show the extent and depth of flooding through the communities and can be used for flood response and recovery efforts by local, county, State, and Federal agencies.

Introduction

Flood information is needed by Federal, State, and local agencies to make informed decisions in meeting mission requirements related to flood hazard mitigation, planning, and response. For example, the Federal Emergency Management Agency (FEMA), U.S. Army Corps of Engineers (USACE), the National Weather Service (NWS) of the National Atmospheric and Oceanic Administration (NOAA), Minnesota Department of Natural Resources (MDNR), Minnesota Department of Public Safety (MDPS) and its division of Homeland Security and Emergency Management (MHSEM) need timely information on the magnitudes and frequency of floods to help respond to flood damage, enhance emergency response management, protect infrastructure, provide recovery guidance from the National Flood Insurance Program and State regulatory programs, and plan for future flood events.

In Minnesota, many of the agencies that need post-flood information are members of a State Hazard Mitigation Team commonly referred to as Silver Jackets. State Silver Jackets chapters are sponsored by the USACE and in Minnesota include as charter members, but is not limited to, the following agencies: USACE, FEMA, MDNR, MHSEM, NWS, and U.S. Geological Survey (USGS).

Heavy rains on June 19–20, 2012, caused severe flooding in northeastern Minnesota and prompted the NWS to issue areal flood, flash-flood, and river flood warnings. The **flood peaks**[1] were exacerbated by a relatively rainy spring, including one of the wettest Mays on record (Minnesota Department of Natural Resources State Climatology Office, 2012a). During the flooding in June 2012, evacuations, water rescues, and road closures were common in communities affected by the flooding. Damages from flooding were extensive and included major transportation disruptions and damage to homes and businesses, dams and flood-control structures, and parks and recreation areas. Damage caused by the flooding resulted in a Presidential Disaster Declaration on July 6, 2012, for the nine counties in northeastern Minnesota affected by the June 19–20, 2012, flood events (Federal Emergency Management Agency, 2012; fig. 1). This disaster declaration also includes a separate storm event in central Minnesota on June 14, 2012, for six counties (Federal Emergency Management Agency, 2012;

[1] Terms in **bold type** are defined in the Glossary at the back of the report.

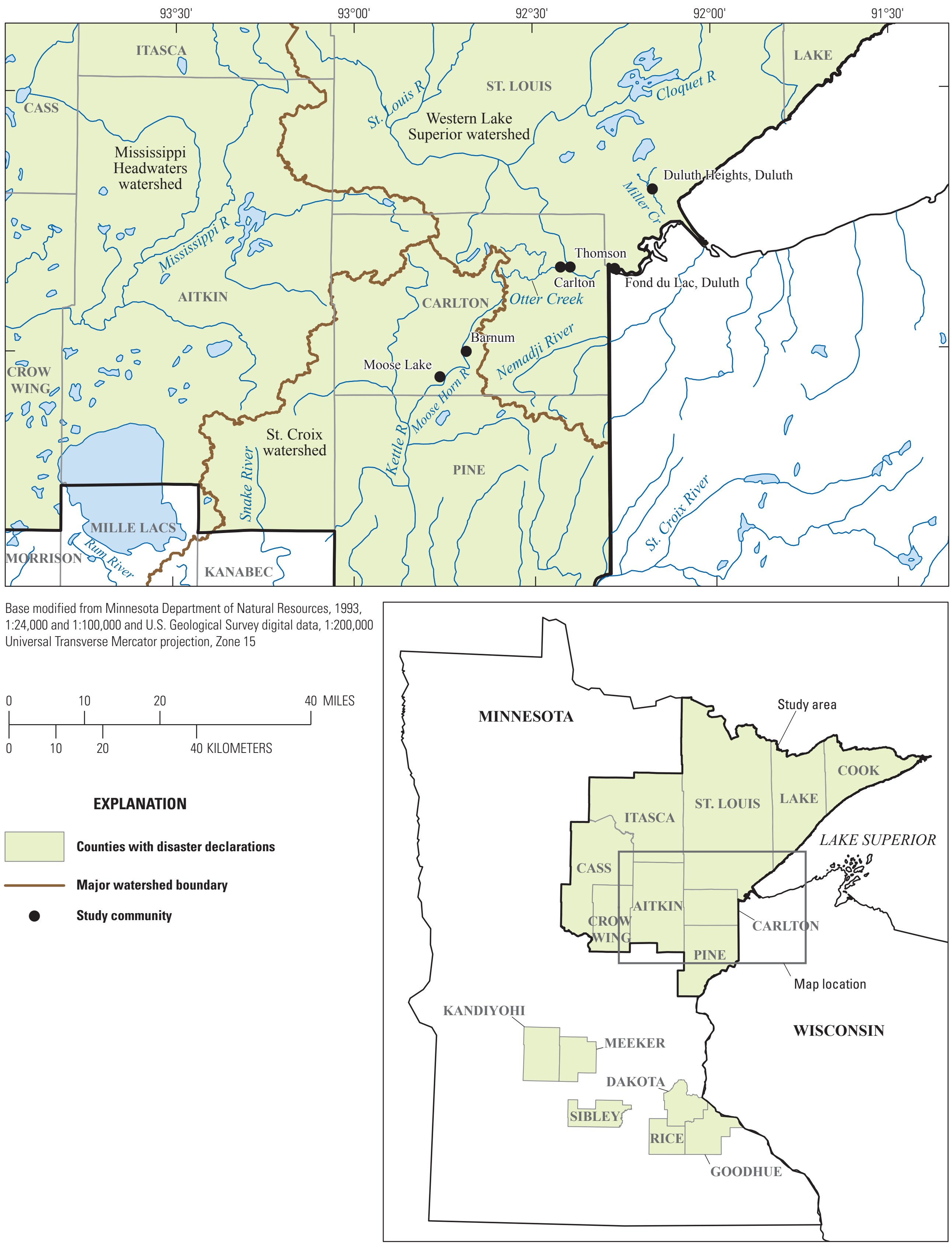


Figure 1. Locations of study communities in the counties with disaster declarations in northeastern Minnesota affected by the June 19–20, 2012, flood events.

Minnesota Department of Natural Resources State Climatology Office, 2012b); however, this report focuses only on the flooding effects in northeastern Minnesota, including the nine contiguous counties of Aitkin, Carlton, Cass, Cook, Crow Wing, Itasca, Lake, Pine, and St. Louis (fig. 1).

Given the severity of the June 2012 flooding in northeastern Minnesota, the USGS, in cooperation with FEMA, lead a study to document the meteorological and hydrologic conditions leading to the flood, and compile flood-peak **gage heights**, **streamflows**, and **annual exceedance probabilities** at USGS **streamgages**. The study also provided data to construct **flood profiles** and flood-peak inundation maps. Flood profiles and flood-peak inundation maps were constructed for six communities in northeastern Minnesota (fig. 1): Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River). The USGS and FEMA collaborated and consulted with Silver Jackets team members extensively in determining locations needing flood documentation.

Purpose and Scope

The purpose of this report is to document the floods of June 2012 in northeastern Minnesota. This report documents the magnitude and extent of flooding and the methods used to define the extent of flooding. **High-water-mark** data were collected after the flood and used to develop flood-peak inundation maps for the six communities most affected by the riverine flooding: Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River). The report summarizes meteorological and hydrologic conditions leading up to the flood. The severity of flooding is put into regional context by computing flood-peak magnitudes and annual exceedance probabilities at 35 USGS streamgages in the counties in northeastern Minnesota with disaster declarations. Flood effects and damages are summarized on the basis of information obtained from FEMA, NWS, MDPS, MHSEM, MDNR, Minnesota Department of Transportation (MnDOT), local agencies, news accounts, photographs, and corroborated testimony from individuals in flood-affected communities.

Conditions Leading to the 2012 Floods in Northeastern Minnesota

The June 2012 flooding in northeastern Minnesota was caused by heavy rainfall on areas that had already received above-normal precipitation. For much of northeastern Minnesota, spring and early summer had the highest total rainfall levels as compared to historical data for the same months (Minnesota Department of Natural Resources State Climatology Office, 2012c). May 2012 was one of the wettest Mays on record in some areas of central and northeastern Minnesota, and was the sixth wettest May on record for Duluth (Minnesota Department of Natural Resources State Climatology Office, 2012a).

In the weeks before the flooding rains of June 19–20, 2012, the ground was saturated from numerous storm systems that delivered 2–4 inches (in.) of rain across parts of northeastern Minnesota. On June 19, 2012, a **warm front** moved in and stalled across northern Minnesota, bringing waves of thunderstorms to the area (Graning and Hluchan, 2012). The heavy rainfall continued until late June 20, 2012, when a **cold front** moved through the area. Carlton County and southern St. Louis County had the highest levels of rainfall, and new records were set in Duluth, including greatest 2-day precipitation with 7.25 in. falling June 19–20, 2012 (Graning and Hluchan, 2012). Local reports of rainfall were as high as 8–10 in. throughout Duluth neighborhoods (Graning and Hluchan, 2012). This June 2012 flood event was the most damaging flood in Duluth's history, surpassing the August 1972 flood event (Minnesota Department of Natural Resources State Climatology Office, 2012d).

A spatial gridded dataset of estimated rainfall totals prepared by the NWS (National Weather Service, written commun., 2012) shows rainfall totals of 7 in. and greater for June 19–20, 2012, in parts of Carlton County and southern St. Louis County (fig. 2). Total rainfall amounts for six NWS Cooperative Observing—Fischer Porter precipitation stations in northeastern Minnesota recorded rainfall totals ranging from 2.73 in. at Eveleth in St. Louis County to 6.27 in. at Sandy Lake in Aitkin County for the storm event on June 19–20, 2012 (fig. 2; table 1). Local direct measurements of rainfall totals may differ from the spatial gridded dataset that is developed from radar data. A seventh Cooperative Observing—Fischer Porter precipitation station is located in Floodwood (not shown) in St. Louis County but was not included in this report because the gage was overtopped during the June rainfall and data were lost.

The cumulative 15-minute rainfall data from the six NWS Cooperative Observing—Fischer Porter precipitation stations (locations shown in fig. 2) indicate the magnitude and timing of the rain that fell throughout the storm events on June 19–20, 2012 (fig. 3). Instantaneous rainfall intensities were as great as 2 to 4 inches per hour (in/h) in the evening of June 19, 2012.

The heavy rains fell on three major watersheds: the Mississippi Headwaters; the St. Croix, which drains to the Mississippi River; and Western Lake Superior, which includes the St. Louis River and other tributaries to Lake Superior (fig. 2). Along the northern shore of Lake Superior, flash flooding was exacerbated by impervious soils and bedrock, and by the steep gradients of streams that drain directly to Lake Superior. In other areas receiving the heavy rainfall, storage from lakes and wetlands delayed and reduced the flood peaks but still resulted in record or near-record floods.

WaterLegacy PTM Objections
Exhibit 31

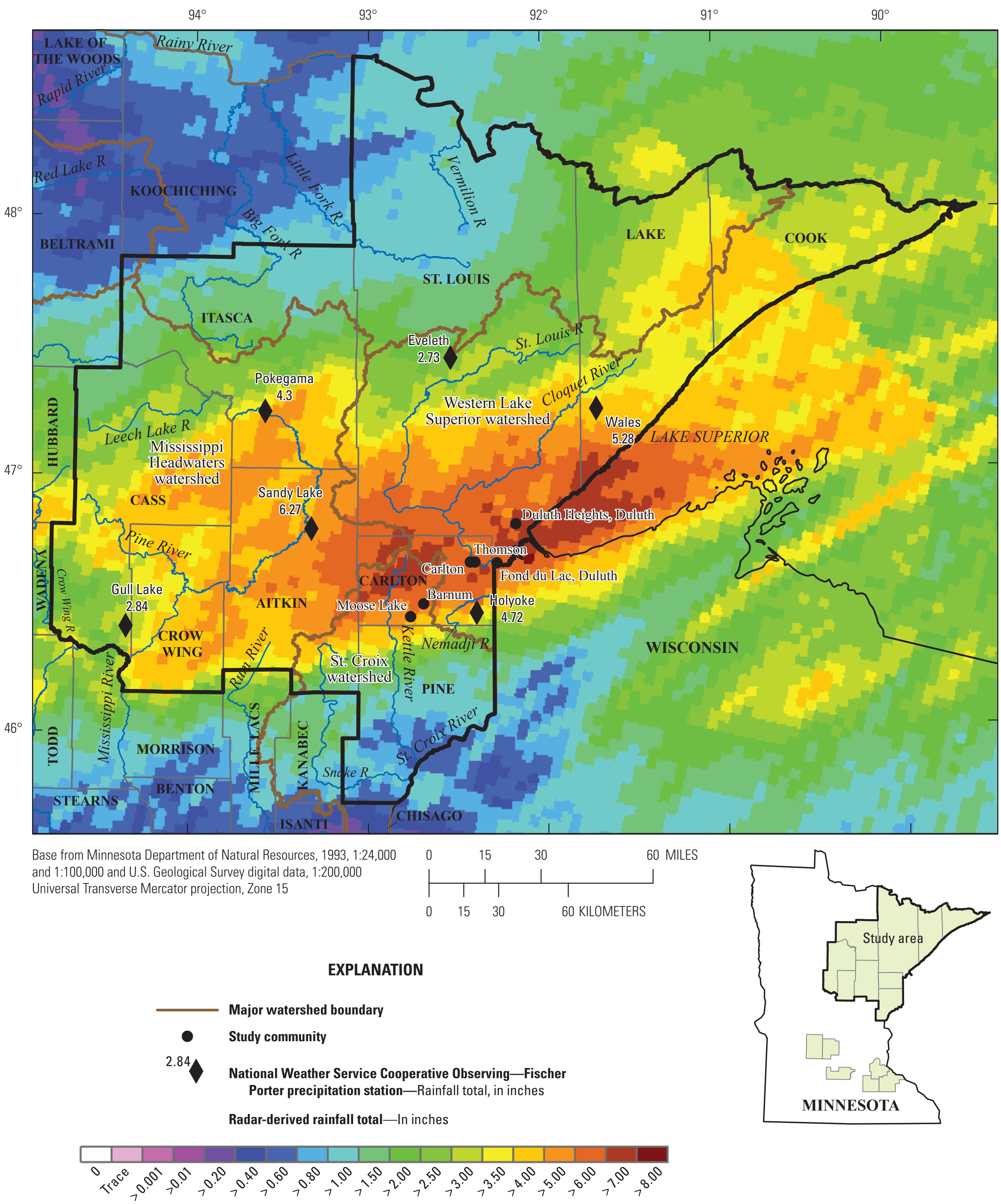


Figure 2. Distribution of 2-day rainfall totals for 7 a.m. Central Daylight Time June 19 through 7 a.m. Central Daylight Time June 21, 2012, and rainfall totals at selected National Weather Service (NWS) Cooperative Observing—Fischer Porter precipitation stations. Rainfall data provided by Steve Gohde and Diane Cooper of the National Weather Service (written commun., 2012).

Table 1. Provisional total rainfall for June 19–20, 2012, at selected National Weather Service (NWS) Cooperative Observing—Fischer Porter precipitation stations in northeastern Minnesota.

[Total rainfall from Steve Gohde and Diane Cooper of the National Weather Service (written commun., 2012). Annual exceedance probabilities from Huff and Angel (1992)]

Precipitation station name (location shown in fig. 2)	County	NWS station identifier	Total rainfall (inches)	48-hour duration rainfall (inches) for selected annual exceedance probabilities[1]				
				0.2	0.1	0.04	0.02	0.01
Eveleth	St. Louis	212645	2.73	3.21	3.74	4.49	5.06	5.63
Gull Lake	Cass	213411	2.84	3.38	3.97	4.86	5.62	6.45
Holyoke	Carlton	213863	4.72	3.53	4.03	4.74	5.36	6.02
Pokegama	Itasca	216612	4.30	3.38	3.97	4.86	5.62	6.45
Sandy Lake	Aitkin	217460	6.27	3.53	4.03	4.74	5.36	6.02
Wales	Lake	218613	5.28	3.21	3.74	4.49	5.06	5.63

[1]The annual exceedance probability is the probability that a given event will be exceeded or equaled in any given year. For example, the annual exceedance probability of the 100-year rainfall is 0.01. In other words, there is a 1-percent chance that the rainfall would be exceeded or equaled in any given year.

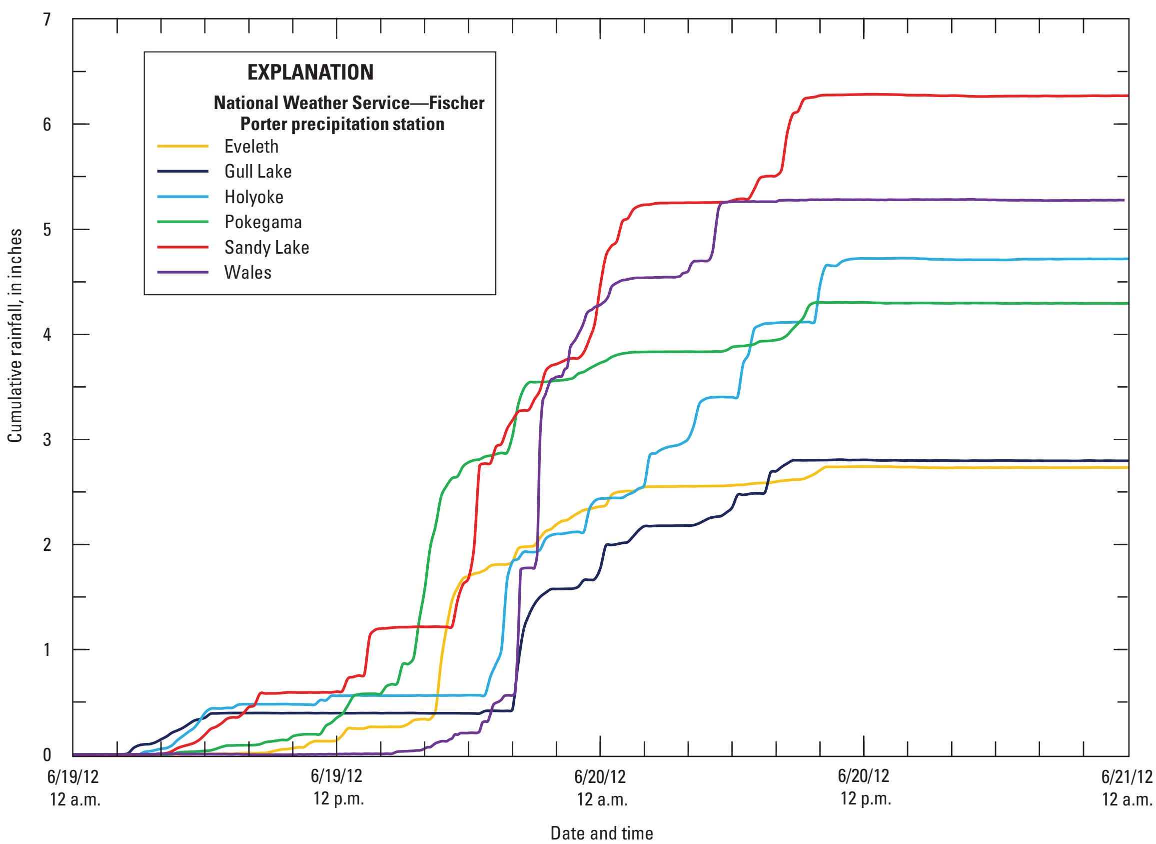


Figure 3. Cumulative daily rainfall during June 19–20, 2012, at selected National Weather Service (NWS) Cooperative Observing—Fischer Porter precipitation stations in northeastern Minnesota.

Methods

The methods used to compute magnitudes and annual exceedance probabilities of peak streamflows and to collect high-water-mark data are described in this section of the report. Methods used to create flood-peak inundation maps and water-surface profiles also are described.

Computing the Magnitudes of Peak Streamflows

Peak streamflows documented in this study were determined at 35 USGS streamgages (19 **continuous-record streamgages** and 16 **crest-stage gages**; locations shown in fig. 4). Continuous-record streamgages record stream levels continuously and for those referred to in this report, data are recorded electronically and telemetered to USGS offices for processing in near real time. Crest-stage gages (CSGs) are partial-record, nonmechanical, nontelemetered gages intended to record only the peak (crest) stream level since the last site visit.

For both types of streamgages, the peak streamflow is determined by an empirical relation developed between the stream level (also referred to as stage or gage height) and streamflow (also referred to as discharge) unique to each location. These stage-discharge relations at streamgages are developed and maintained by relating paired measurements of stage (gage height) and streamflow over the range of streamflows through time. Paired measurements used to develop a stage-discharge relation are determined most commonly by direct measurement of stage (observed/recorded) and streamflow (velocity meter) at the streamgages (Rantz and others, 1982); or, if direct measurement is not possible, by indirect hydraulic methods (Benson and Dalrymple, 1967). The stage-discharge relation is developed using available stage/discharge measurements and controlling hydraulic features of the channel. Stage-discharge relations can be extrapolated slightly beyond the highest measurement of stage/streamflow, depending on available information about channel geometry and hydraulic conditions (Rantz and others, 1982).

Flood-peak gage heights were obtained either from electronic data recorders at continuous-record streamgages or from CSGs. At both types of streamgages, peak gage heights were confirmed by independent secondary streamgages or by nearby high-water marks left as the streams receded from flood peak. At a few streamgages that were inundated by flood waters, peak gage heights were determined from surveyed high-water marks near streamgages. The stage-discharge relation at each streamgage was used to compute peak streamflow from the flood-peak gage height. Direct or indirect streamflow measurements served as flood-event data points for stage-discharge relation verification and extrapolation.

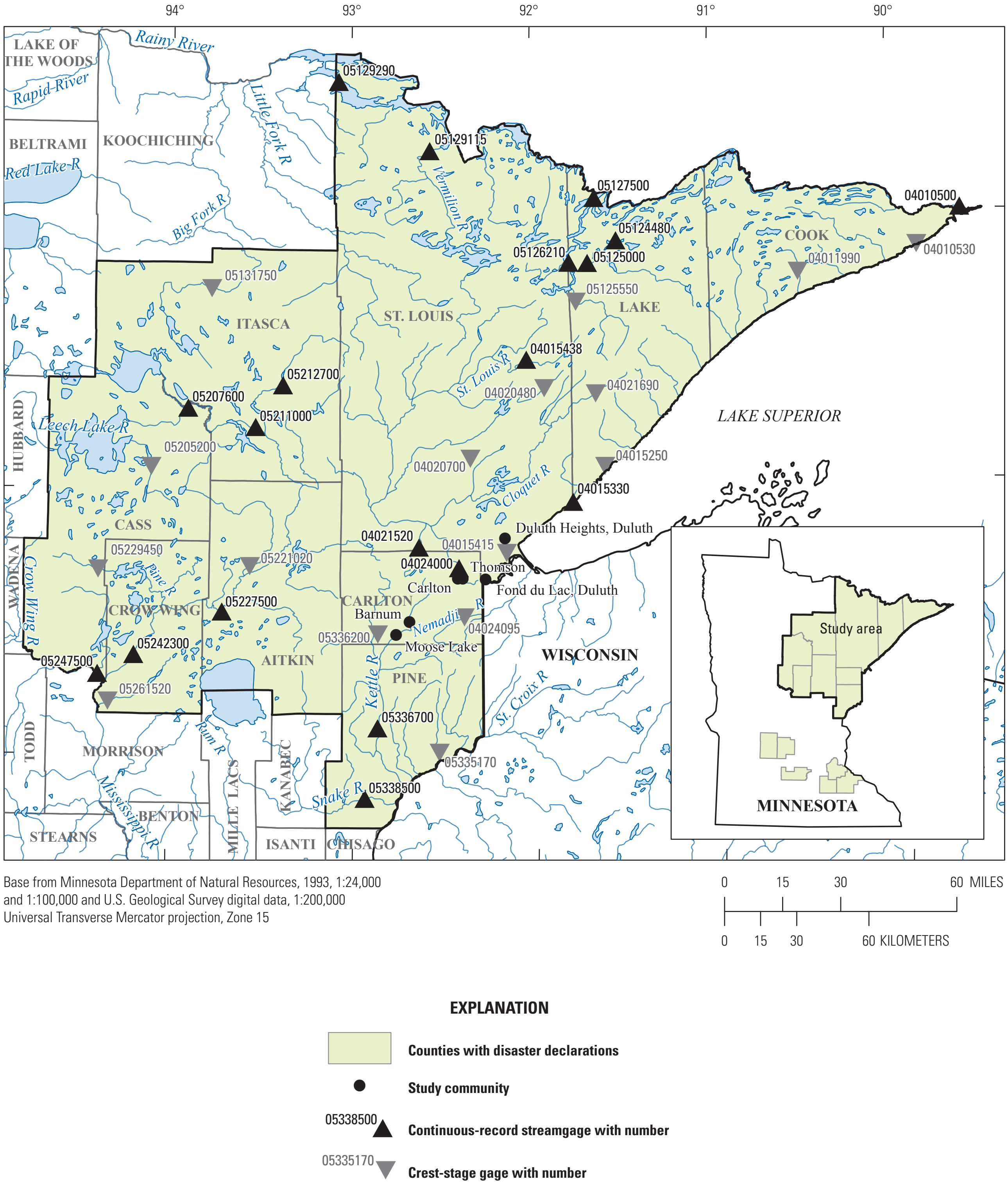
Estimating Annual Exceedance Probabilities of Peak Streamflows

The annual exceedance probability (AEP) for a particular streamflow is the probability of that streamflow being equaled or exceeded in any given year. An AEP of 0.01 has a 1 in 100 chance or 1-percent risk of being equaled or exceeded in any given year (Holmes and Dinicola, 2010). The AEP is related to the traditional concept of **recurrence interval**; by definition, the recurrence interval corresponding to a particular AEP is equal to 1 divided by the AEP (American Society of Civil Engineers, 1953; Holmes and Dinicola, 2010).

Streamflows for selected AEPs (0.10, 0.04, 0.02, 0.01, and 0.002) were estimated by using one of four methods: (1) the Bulletin 17B procedure presented by the Interagency Advisory Committee on Water Data (1982), (2) regional regression equations for rural conditions developed by Lorenz and others (2010), (3) the Expected Moments Algorithm (Cohn and others, 1997), or (4) weighting of independent estimates (WIE) procedure (Cohn and others, 2012; Interagency Advisory Committee on Water Data, 1982). Users of the Bulletin 17B procedure and regional regression equations for rural conditions calculate flood probabilities by fitting systematic annual peak-streamflow data to a log-Pearson type III (LPIII) distribution. The Expected Moments Algorithm is a generalization of the procedures in Bulletin 17B and was designed to better accommodate historical peak-flow data (known peak flows outside the period of continuous streamflow data collection) and left-censored data (peak flows less than what can be measured at the streamgage). The WIE method is used to reduce uncertainty in the AEP by combining the at-site estimate with the regional regression estimate from Lorenz and others (2010) for records at sites that are unregulated, unaffected by urbanization, and have a drainage area less than 3,000 square miles (mi^2) (Lorenz and others, 2010; Cohn and others, 2012). The June 2012 peak streamflows can then be related to the AEPs for each streamgage, by bracketing the observed streamflow with the streamflow magnitudes associated with the selected AEPs.

Collection of High-Water-Mark Data

High-water marks record the observed elevation of the flood peak, and provide the data needed to estimate the maximum flood-inundation surface. High-water marks were identified and flagged to document inundation levels in selected communities most affected by flooding, in addition to the high-water marks described previously that were collected at streamgages to confirm peak discharges. These high-water marks were collected by staff from the USGS, USACE, and city of Duluth in northeastern Minnesota during June and July 2012 after floodwaters had receded. To ensure consistent methods were used to identify and document high-water marks, USGS staff met with and provided other agency staff with documentation of the methods used.



Base from Minnesota Department of Natural Resources, 1993, 1:24,000 and 1:100,000 and U.S. Geological Survey digital data, 1:200,000
Universal Transverse Mercator projection, Zone 15

Figure 4. Locations of selected U.S. Geological Survey streamgages in the counties with disaster declarations for the floods of June 2012 in northeastern Minnesota.

Common high-water marks included stain lines and debris buildup on buildings, trees, or other structures that identify the highest level reached by the flooding waters. The quality of the high-water marks was subjectively rated in the field as excellent, good, fair, or poor by the high-water-mark crews. Ratings were based on the clarity of the mark and visual or hand-level comparison to nearby marks.

The high-water marks collected by the USGS were surveyed using Real-Time Kinematic Global Positioning System (RTK-GPS). The survey used a network of continuously operating global positioning system (GPS) stations, known as the MnDOT CORS Network (*http://www.dot.state.mn.us/surveying/CORS/CORS.html*), that provides real-time correction to the rover GPS through a cellular data connection, thus eliminating the need for a base station setup. Each survey was calibrated to a nearby MnDOT benchmark. Benchmarks were chosen based on the vertical accuracy rating of order 2 or better, as the vertical position of the high-water-mark data was deemed most critical. In the case of Carlton, Thomson, and Moose Lake, the horizontal order of the nearby usable benchmarks were not established. The horizontal position of the RTK-GPS survey was then adjusted using a noncalibrated GPS measurement at the benchmark or visual correction from aerial imagery.

The preferred method of surveying was to set the RTK-GPS rover up directly above the high-water mark. However, in many cases tree cover or building interference did not allow direct surveying of the high-water mark, and then a survey point was made a short distance away by transferring the elevation of the desired high-water mark to the survey point by using a hand level or string level. No correction for horizontal position was made. All USGS high-water marks were surveyed to an estimated vertical accuracy of 0.1 foot (ft), whereas the horizontal position may vary by as much as 15 ft.

The city of Duluth and the USACE Detroit District collected and surveyed high-water marks along Keene Creek (not shown), Kingsbury Creek (not shown), and Miller Creek, including in the Duluth Heights neighborhood of Duluth, using methods similar to the USGS collection and surveying methods. The USACE St. Paul District also provided high-water marks that are routinely collected during flood events, primarily at bridge structures and along roads, along selected rivers in the Mississippi and Kettle River Basins. The methods and accuracy of these data were not determined in this study. All high-water-mark data are included in appendix 1; table 1–1 contains the high-water marks for mapped communities of Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River), and table 1–2 contains the high-water marks for additional areas in northeastern Minnesota.

Flood-Peak Inundation Maps

Flood-peak inundation maps were produced from the high-water marks to show the extent and depth of the peak flooding. These maps were produced by use of geographic information system (GIS) software and associated programs (Morlock and others, 2008; Fitzpatrick and others, 2008; Fowler and others, 2010; Ellison and others, 2011), and a detailed description of the GIS process is described by Mastin and others (2010). The GIS layers of high-water-mark locations and elevations were used in conjunction with LiDAR-based 1-meter land-surface elevation data files. LiDAR, an acronym for “light detection and ranging,” is remote sensing technology that is based on discrete light pulses and measured traveltimes. It is used to generate highly accurate three-dimensional representations of the Earth’s surface, termed “digital elevation models” (DEMs) (National Oceanic and Atmospheric Administration, 2008). These DEMs were used to develop the inundation maps, which then were superimposed on the corresponding National Agricultural Imagery Program aerial imagery (U.S. Department of Agriculture, 2010). Note that LiDAR topography represents “bare earth” elevations, such that houses in the flood plain and bridge decks over the river centerline are removed. Additionally, LiDAR measurements do not penetrate water, so the elevation in water bodies approximately represents the water surface at the time of the LiDAR collection flights.

Water-surface elevation was assigned to the stream centerline based on nearby high-water-mark data with a linear interpolation along the stream centerline between adjacent high-water marks. However, the actual water surface may have had a different profile than the linear interpolation, hence the inundation may have been somewhat different than the mapped results. This is especially true at structures where no high-water-mark data were available; there may have been a sharper drop in the water-surface profile from the upstream to downstream side of a culvert or bridge structure. Cross-section lines were drawn across the valley representing a line of equal, potential peak water-surface elevation and, generally, were perpendicular to the direction of flow. A potential water-surface elevation was assigned to each cross section based on the water-surface elevation of the stream where they intersect. A triangular irregular network (TIN) was produced from the cross-section lines to produce a three-dimensional potential water surface. The terrain elevation (DEM) was subtracted from the potential water-surface elevation TIN, resulting in a GIS coverage where positive values represent the depth of inundation.

Flood-Peak Water-Surface Profiles

Standard USGS methods were used to develop flood-peak water-surface profiles from the high-water-mark elevations and locations (Benson and Dalrymple, 1967; Lumia and others, 1986). Flood profiles were produced for the mapped stream reaches for the six severely affected communities in northeastern Minnesota by plotting high-water-mark elevations by mile of stream as measured upstream on the centerline of the **thalweg** from the downstream boundary of each study reach. Because the flood-inundation in Thomson represented flow across the landscape, the profile was measured along an approximate centerline of the flow rather than along the nearby stream thalweg. The water surface between high-water marks was estimated by linear interpolation. A linear interpolation between high-water marks is an approximation of the actual water surface.

Floods of June 2012 in Northeastern Minnesota

The estimated AEPs of peak streamflows for the floods of June 2012 are presented in this section of the report. Flood-peak inundation maps and flood-peak water-surface profiles also are presented.

Magnitudes and Estimated Annual Exceedance Probabilities of Peak Streamflows

The magnitudes (flood-peak gage-height data and peak-streamflow data) and estimated AEPs from the June 2012 floods are presented for 34 of the 35 streamgages (table 2). The Mississippi River at Willow Beach at Ball Club (streamgage 05207600) does not have sufficient historical record to compute AEPs, and the basin characteristics are beyond the range applicable by the regression equations. New peak-of-record streamflows were recorded at 13 USGS streamgages as a result of the heavy rainfall, including the St. Louis River at Scanlon (streamgage 04024000), which has more than 100 years of streamflow records. Flood-peak streamflows in June 2012 had AEPs estimated to be less than 0.002 (0.2 percent; recurrence interval greater than 500 years) for five streamgages, and between 0.002 and 0.01 (1 percent; recurrence interval greater than 100 years) for four streamgages (table 2).

The timing of peak flows for streams of differing size is evident in the plot of the stage hydrographs for selected streamgages for the flood event (fig. 5). Streams and smaller rivers were quick to respond to the intense rainfall, such as the Knife River near Two Harbors (04015330), which peaked at an estimated 25,000 cubic feet per second (ft^3/s) on June 20, 2012, exceeding the previous peak of record of 7,440 ft^3/s from May 1979 (table 2). Some larger rivers also had rapid rises in streamflow in response to the intense rainfalls late on June 19, 2012, such as the St. Louis River at Scanlon (04024000), which peaked at 45,300 ft^3/s on June 21, 2012 (table 2). Other large rivers, such as the Mississippi River, had a more delayed response time as the water accumulated from tributaries; the peaks also were affected by dam and reservoir management activities (fig. 5).

Flood-Peak Inundation Maps and Water-Surface Profiles

Flood-peak inundation maps (figs. 2–1 to 2–6 in appendix 2) and flood-peak water-surface profiles (figs. 3–1 to 3–6 in appendix 3) were produced for the six communities of Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River), respectively. Personnel from the USGS, USACE Detroit District, and city of Duluth flagged and surveyed high-water marks in June and July 2012 in these six most severely affected communities. The city of Duluth and the USACE Detroit District also surveyed high-water marks along Keene Creek (not shown), Kingsbury Creek (not shown), and the lower part of Miller Creek. The USACE St. Paul District collected high-water marks at bridge structures along the Mississippi River and Diversion Channel in the Mississippi River Basin, and along the Moose Horn, Kettle, Pine, and Willow Rivers in the Kettle River Basin. Descriptions of all the high-water marks are listed in appendix 1; only the locations of high-water marks in the six mapped communities are shown in the report figures.

A flood-peak inundation map was generated for each community showing the maximum extent and depth of floodwaters in and around the community (appendix 2). Inundation maps contain locations and elevations of the high-water marks, along with an indication of whether each high-water mark was used to develop the flood-peak water-surface. If a data point was substantially higher or lower when compared to neighboring points, the point in question was not used in interpolating the water surface for the inundation map. For example, high-water marks MOOSE1 and MOOSE2 (table 1–1) in the community of Moose Lake were substantially lower than other high-water marks in the area and were not used to interpolate the water surface for mapping the flood inundation (figs. 2–5 and 3–5). It is assumed that these marks were left as flood waters receded and were not representative of the peak water surface. In the Fond du Lac neighborhood of Duluth, numerous high-water marks were collected in proximity to each other; however, the elevations do not agree in connecting a single peak water-surface profile along the St. Louis River (figs. 2–4 and 3–4). The elevations from high-water-mark identifiers FDL1, FDL3, and FDL10 were used in the flood-inundation mapping for the upstream part of the profile, whereas the other nearby high-water marks that are all lower in elevation and likely not representative of the peak water surface were disregarded. Additionally, high-water-mark identifier FDL9 was on a hill with substantial flow heading downslope towards the St. Louis River, and was not used for the water-surface profile along the St. Louis River.

Table 2. Provisional flood-peak gage heights, peak streamflows, and annual exceedance probabilities of peak streamflows during the floods of June 2012 at selected U.S. Geological Survey streamgages in northeastern Minnesota.

[mi², square miles; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; WY, water year; ft³/s, cubic feet per second; %, percent; Minn., Minnesota; e, estimated, >, greater than; <, less than; --, data not available]

Station number	Stream and community	Drainage area (mi²)	Gage vertical datum (ft above NGVD 29)	Water years[1] with peak-flow records	Length of record of annual peaks (years)	Peak flow for period of record prior to WY 2012			Peak flow for June 19–30, 2012 floods			Annual exceedance probability[2] for June 2012 peak streamflow	Estimated streamflow of 0.01 (1%) annual exceedence probability
						Date	Gage height (ft above gage datum)	Stream-flow (ft³/s)	Date	Gage height (ft above gage datum)	Stream-flow (ft³/s)		
04010500	Pigeon River at Middle Falls near Grand Portage, Minn.	609	787.58	1924–2011	88	5/5/1934	7.60	11,000	6/20/2012	8.76	3,700	> 0.10	[3]11,700
[4]04010530	Reservation River near Hovland, Minn.	16.5	660.00	1991–92, 2000–11	14	7/31/2009	3.68	> 1,350	6/20/2012	4.05	1,300	0.10–0.04	[5]2,130
[4]04011990	Cascade River at Forest Road 45 near Grand Marais, Minn.	87.6	1,500.00	1985–2011	27	4/24/2001	13.36	1,810	6/20/2012	11.38	[6]671	> 0.10	[5]2,590
[4]04015250	Silver Creek tributary near Two Harbors, Minn.	3.62	Undetermined[7]	1965–2011	47	9/20/1972	17.08	1,880	6/20/2012	17.50	[8]2,200	0.01–0.002	[5]1,890
04015330	Knife River near Two Harbors, Minn.	83.6	Undetermined[7]	1975–2011	37	5/10/1979	11.16	7,440	6/20/2012	12.81	[8,9]25,000	< 0.002	[5]9,920
[4]04015415	Lake Superior tributary at West 9th Street in Duluth, Minn.	1.81	Undetermined[7]	2001–11	11	8/2/2010	9.72	175	6/20/2012	11.61	[8]740	< 0.002	[10]226
[11]04015438	St. Louis River near Skibo, Minn.	101	1,500.00	--	--	--	--	--	6/24/2012	20.79	[8]813	> 0.10	[12]1,800
[4]04020480	North Branch Whiteface River near Fairbanks, Minn.	17.1	Undetermined[7]	1979–2011	33	4/23/1979	13.67	660	6/21/2012	13.90	649	0.02–0.01	[5]700
[4]04020700	Bug Creek at Shaw, Minn.	24.8	Undetermined[7]	1979–2011	33	7/5/1999	18.00	[9]1,350	6/21/2012	18.10	[8]1,580	0.01–0.002	[5]1,380
04021520	Stoney Brook at Pine Drive near Brookston, Minn.	74.0	Undetermined[7]	2005–11	7	4/27/2008	7.70	453	6/21/2012	12.34	[8]1,170	0.02–0.01	[12]1,290
[4]04021690	Cloquet River near Toimi, Minn.	40.8	1,700.00	1986–2011	26	7/4/1993	9.06	1,540	6/21/2012	8.30	1,110	0.04–0.02	[5]1,460
04024000	St. Louis River at Scanlon, Minn.	3,430	1,101.23	1908–2011	104	5/9/1950	--	[13]37,900	6/21/2012	16.62	[8]45,300	< 0.002	[3]38,400
[4]04024095	Nemadji River near Holyoke, Minn.	127	756.12	1972–2011	40	8/3/2011	18.60	5,300	6/20/2012	21.05	[8,9]9,700	< 0.002	[5]5,830
05124480	Kawishiwi River near Ely, Minn.	254	Undetermined[7]	1967–2011	45	5/4/2001	6.07	1,870	6/24/2012	4.91	793	> 0.10	[5]2,540
05125000	South Kawishiwi River near Ely, Minn.	--	1,430.00	1952–61, 1976–78, 2003–11	22	4/21/1976	7.18	4,980	6/26/2012	5.69	2,560	> 0.10	[10]8,000
[4]05125550	Stony River near Babbitt, Minn.	215	Undetermined[7]	1976–80, 1986–2011	31	4/19/1976	8.71	2,490	6/26/2012	7.31	1,480	> 0.10	[5]3,090
05126210	South Kawishiwi River above White Iron Lake near Ely, Minn.	837	Undetermined[7]	1976–78, 2003–11	12	4/22/1976	11.42	8,080	6/26/2012	9.49	4,890	> 0.10	[3]12,700
05127500	Basswood River near Winton, Minn.	1,740	1,296.80	1926–27, 1930–2011	84	5/24/1950	6.94	[13]15,600	6/30/2012	5.59	4,370	> 0.10	[3]12,400
05129115	Vermilion River near Crane Lake, Minn.	905	1,180.00	1979–2011	33	4/1979	15.15	4,600	6/21/2012	10.20	[6]1,520	> 0.10	[5]5,660
05129290	Gold Portage outlet from Kabetogama Lake near Ray, Minn.	--	Undetermined[7]	1983–94, 1998–2011	26	5/29/2001	([14])	1,310	6/21/2012	18.38	[6]770	> 0.10	[3]1,320
[4]05131750	Big Fork River near Bigfork, Minn.	606	Undetermined[7]	1973–2011	38	4/22/1979	15.48	2,830	6/21/2012	< 10.59	[6]< 783	> 0.10	[5]3,150
[4]05205200	Boy River near Remer, Minn.	289	Undetermined[7]	1986–2011	26	7/23/1987	11.64	660	6/22/2012	11.14	420	> 0.10	[5]1,040
05207600	Mississippi River at Willow Beach at Ball Club, Minn.	2,850	Undetermined[7]	2008–11	4	2/18/2011	[14, 15]11.50	[13]2,720	6/24/2012	8.71	[6]1,410	Undetemined[16]	Undetemined[16]
05211000	Mississippi River at Grand Rapids, Minn.	3,370	1,242.03	1942–2011	70	9/3/1948	15.20	[13]12,500	6/19/2012	8.41	[6]3,190	> 0.10	[10]4,740
05212700	Prairie River near Taconite, Minn.	371	1,294.81	1968–83, 2001–11	27	4/17/1969	11.81	3,260	6/27/2012	7.91	[6]942	> 0.10	[5]4,860

Table 2. Provisional flood-peak gage heights, peak streamflows, and annual exceedance probabilities of peak streamflows during the floods of June 2012 at selected U.S. Geological Survey streamgages in northeastern Minnesota.—Continued

[mi², square miles; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; WY, water year; ft³/s, cubic feet per second; %, percent; Minn., Minnesota; e, estimated, >, greater than; <, less than; --, data not available]

Station number	Stream and community	Drainage area (mi²)	Gage vertical datum (ft above NGVD 29)	Water years[1] with peak-flow records	Length of record of annual peaks (years)	Peak flow for period of record prior to WY 2012			Peak flow for June 19–30, 2012 floods			Annual exceedance probability[2] for June 2012 peak streamflow	Estimated streamflow of 0.01 (1%) annual exceedence probability
						Date	Gage height (ft above gage datum)	Stream-flow (ft³/s)	Date	Gage height (ft above gage datum)	Stream-flow (ft³/s)		
[4]05221020	Willow River below Palisade, Minn.	523	Undetermined[7]	1972–2011	40	4/25/1979	17.25	3,730	6/28/2012	17.43	3,440	0.10–0.04	[5]4,820
05227500	Mississippi River at Aitkin, Minn.	6,140	1,182.41	1888–99, 1902–2011	112	5/20/1950	22.49	[13]20,000	6/28/2012	18.71	15,100	0.04–0.02	[3]16,400
[4]05229450	Pine River near Pine River, Minn.	261	1,279.00	1986–2011	26	5/14/1999	5.15	1,520	6/23/2012	5.74	[8,9]2,000	0.01–0.002	[5]1,900
05242300	Mississippi River at Brainerd, Minn.	7,320	1,146.96	1988–2011	24	4/30/2001	16.70	[13]17,500	6/28/2012	17.61	[8]17,900	0.02–0.01	[10]19,100
05247500	Crow Wing River near Pillager, Minn.	3,760	1,151.00	1965, 1969, 1970–2011	43	4/14/1965		[13]18,300	6/24/2012	7.35	[6]6,860	> 0.10	[3]20,600
[4]05261520	Nokasippi River near Fort Ripley, Minn.	193	Undetermined[7]	1986–2011	26	6/26/2003	15.17	1,160	6/22/2012	15.10	[8]1,200	0.10–0.04	[5]1,740
[4]05335170	Crooked Creek near Hinckley, Minn.	94.4	Undetermined[7]	1986–2011	26	4/23/2001	16.65	2,100	6/22/2012	15.02	[6]1,380	> 0.10	[5]2,790
[4]05336200	Glaisby Brook near Kettle River, Minn.	27.0	1,105.00	1960–2011	52	7/22/1972	10.18	1,370	6/20/2012	12.26	[8,9]> 2,000	0.01–0.002	[5]1,520
05336700	Kettle River below Sandstone, Minn.	868	931.50	1965, 1968–2011	45	7/23/1972	15.38	17,200	6/22/2012	18.22	[8]24,800	< 0.002	[5]17,900
05338500	Snake River near Pine City, Minn.	974	Undetermined[7]	1914–17, 1950, 1952–2011	61	7/27/1972	10.38	14,300	6/26/2012	5.66	[6]2,930	> 0.10	[5]15,300

[1]A water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends. For some sites, records include annual peak-flow data only.

[2]The annual exceedance probability is the probability that a given event magnitude will be equaled or exceeded in any given year and is the reciprocal of the recurrence interval. The recurrence interval is the average interval of time within which the given flood will be equaled or exceeded once (American Society of Civil Engineers, 1953, p. 1221). The annual exceedance probability for a recurrence interval of 10 years is 0.10 (10%); for 25 years, 0.04 (4%); for 50 years, 0.02 (2%); and for 100 years, 0.01 (1%).

[3]Streamflow computed from Expected Moments Algorithm (Cohn and others, 1997).

[4]U.S. Geological Survey crest-stage or peak-stage gage.

[5]Streamflow from weighting of independent estimates (WIE) procedure (Interagency Advisory Committee on Water Data, 1982, appendix 8). The independent estimates were based on Lorenz and others (2010).

[6]June 2012 peak was not peak of water year 2012.

[7]Elevation from vertical datum has not been established.

[8]New streamflow peak of record.

[9]Streamflow is an estimate.

[10]Streamflow computed from Bulletin 17B, Guidelines for Determining Flood Flow Frequency (Interagency Advisory Committee on Water Data, 1982).

[11]Streamgage was installed August 2011.

[12]Streamflow from Lorenz and others (2010) regression equations.

[13]Streamflow affected to unknown degree by regulation or diversion.

[14]Gage height not the maximum for the year.

[15]Gage height affected by backwater.

[16]Recurrence-interval flows have not been established. One or more basin characteristics are beyond the range used for development of models from regression analysis.

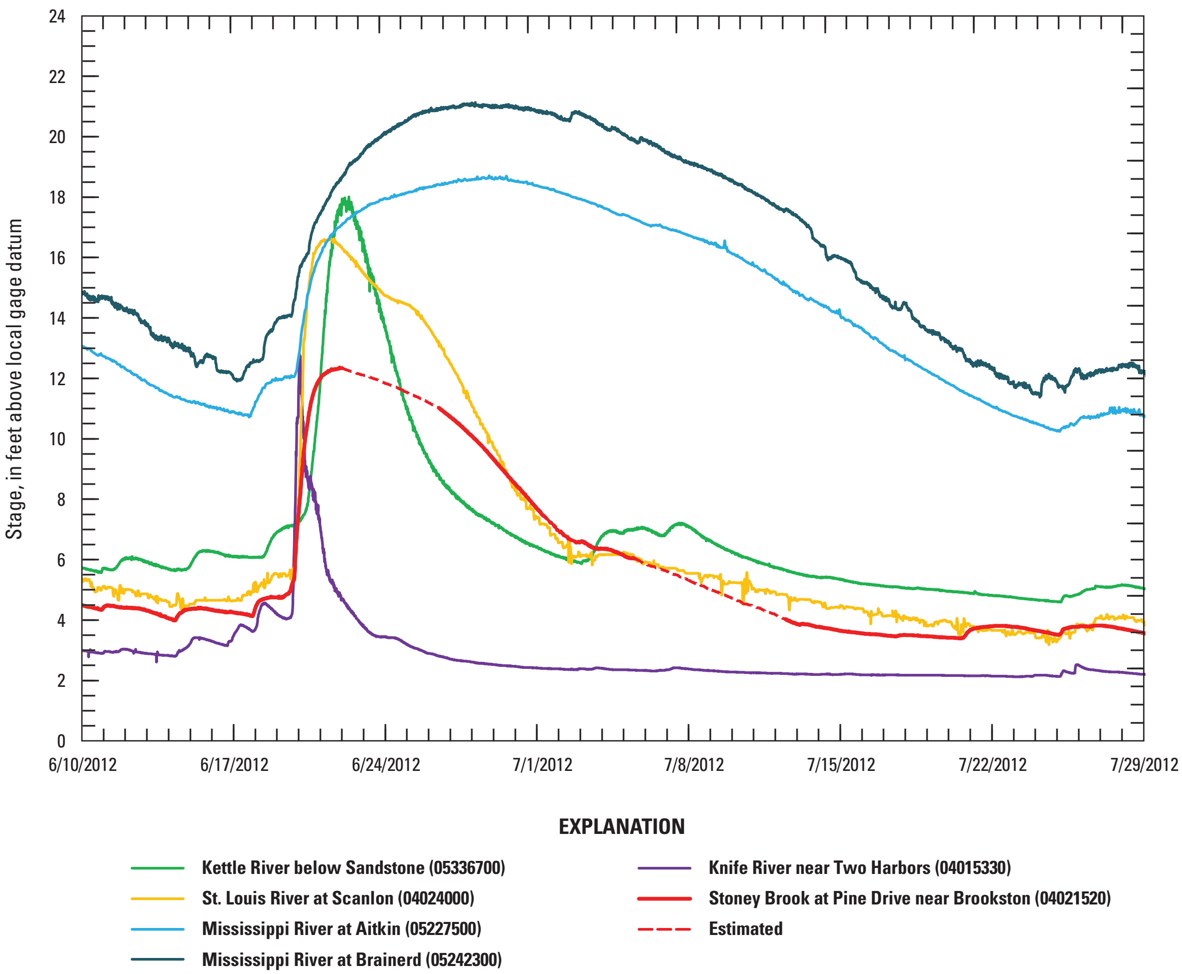


Figure 5. Provisional stage hydrographs at selected U.S. Geological Survey streamgages in northeastern Minnesota for June 10 through July 29, 2012.

The maps were checked by USGS surveying and high-water-mark personnel, and the high-water marks were compared spatially to check for mathematical or other errors. Anecdotal information from local residents was used to interpret the water-surface profile between high-water marks and to extrapolate the area of inundation beyond the surveyed area as necessary. The maps also were visually compared to photographs and videos of flooding available online and from local residents, as well as aerial photographs taken by MnDOT personnel from a helicopter during the flooding. Not all photographs and videos were taken during peak flooding and they are indicative of the minimum area that was flooded. Aerial photographs were used to extrapolate the maps beyond the extent of surveyed high-water marks; for example, the inundation in Fond du Lac neighborhood of Duluth extended downstream and to the north away from the river corridor where most high-water marks were found and surveyed. The elevation and extent of the flood waters were inferred from the MnDOT aerial photographs at easily identifiable edges of water across the roadways.

Flood-peak water-surface profiles were produced from the high-water-mark data along the thalweg (appendix 3). The profiles include only the high-water marks that were used to determine the elevation of the flood-peak water-surface (appendix 2). The only exception is that the water-surface profile for Thomson does not include high-water-marks ETHOM1 and ETHOM2, which were used to map the water-surface elevation of the east side of town but are not adjacent to the primary flow path that is represented in the water-surface profile (figs. 2–6 and 3–6). Flood-peak profiles show how the flood-peak inundation surface and slope varied along the stream reach through each of the six communities. Locations of bridge crossings were added to the profiles to provide additional context.

Although few high-water marks were identified in Barnum (fig. 2–1), photographs taken by residents during the floods also provided information on what areas of town were flooded by the Moose Horn River. Southwest of town, inundation was mapped by assuming that floodwaters spilled out of the channel and backed up this drainage area that normally flows north into the Moose Horn River during low-flow conditions.

The city of Carlton also is located near Thomson Reservoir; however, flooding in Carlton originated from Otter Creek on the south side of town. Otter Creek flows east until it joins the St. Louis River downstream of Thomson Reservoir. As the floodwaters in Otter Creek rose, they spilled northward across the train tracks and flowed through town along two pathways (fig. 2–2). The floodwaters likely flowed north of town, then turned and flowed east along a drainage path south of Thomson Reservoir.

The flooding in the Duluth Heights neighborhood in Duluth was from Miller Creek, and affected businesses along Miller Trunk Highway (fig. 2–3). Parts of Miller Trunk Highway were inundated and the road was temporarily closed.

Also in Duluth, the Fond du Lac neighborhood was substantially inundated by the St. Louis River (fig. 2–4). Floodwaters inundated most residences along the north side of the river. Highway 23 was underwater in several locations and was closed to traffic.

The town of Moose Lake was flooded along Moosehead Lake on the Moose Horn River (fig. 2–5). Much of the rain that contributed to flooding in Moose Lake fell on the contributing watershed farther upstream. The Moose Horn River enters the northeast corner of Moosehead Lake, and exits in its southwest corner. The Portage River also is tributary to Moosehead Lake, entering at the east side. The water surface of the lake was mapped at an elevation of 1,052.5 ft for the entire area of the expanded lake. Floodwaters inundated houses, schools, and a campground.

The St. Louis River exits Thomson Reservoir (fig. 2–6) at the dam west of the town of Thompson. Although the flooding along the St. Louis River washed out part of the Highway 210 roadway, this area was not in the study area for inundation mapping. Floodwaters spilled out of Thomson Reservoir at several small dam structures and flowed overland into the town of Thomson. The more destructive floodwaters flowed overland and south along Vermillion Street, flooding houses and causing substantial damage to the street. This water continued to flow southeast across Highway 210 and joined the St. Louis River south of the study limit (fig. 2–6). On the eastern side of Thomson, the floodwaters flowed down the forested hill from the reservoir and flooded houses along Dalles Avenue. Two culverts at the study boundary (indicated by the deeper inundation depths at the southern study boundary on fig. 2–6) could not pass all the flow to the south, which backed up water and caused it to flow west along Dalles Avenue and join with the floodwaters from Vermillion Street. Farther to the east, a diversion canal that conveys water from Thomson Reservoir downstream to Minnesota Power facilities also was beyond the study limit.

Description of Flood Damages and Effects

Heavy rainfall on already saturated land caused widespread flash flooding and river flooding in northeastern Minnesota in June 2012. Transportation disruptions were widespread, and road closures were common across Itasca, Aitkin, Carlton, southern Lake, and southern St. Louis Counties. Damages included residences, infrastructure, businesses, public parks, and recreation facilities. The most severely affected communities, and the focus of this study for inundation mapping, included Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River). Nearby communities such as Floodwood (not shown), Fond du Lac Indian Reservation (not shown), and Cloquet (not shown) also received extensive flooding and damage and were inspected by field crews but were beyond the scope of this study and not surveyed for high-water marks.

The floods in northeastern Minnesota caused more than an estimated $100 million dollars in damages. Following is a summary of damage assessment compiled after June 2012 primarily from news releases and information by the Minnesota Department of Public Safety, Homeland Security and Emergency Management (2012):

- Road closures included Interstate 35 through Duluth and south of Carlton, as well as numerous State highways and local roads.
- Evacuations included Barnum, Thomson, and part of Moose Lake (Carlton County), parts of Fond du Lac neighborhood of Duluth, and Willow River (not shown; Pine County).
- Evacuation sites were set up in Duluth, Carlton, Scanlon (not shown), and Askov (not shown).
- Red Cross staffed evacuation sites, and Salvation Army provided meals.
- Food and drinking-water distribution points were set up in the affected areas.
- The Lake Superior Zoo in Duluth experienced damage as Kingsbury Creek (not shown) flooded, including the loss of 14 animals and damage of structures. Several other animals were swept from their enclosures but were safely rescued (Lake Superior Zoo, 2012).
- Jay Cooke State Park (not shown) was closed due to severe damage to the entrance route on Highway 210. The park's iconic swinging bridge over the St. Louis River was severely damaged.
- Other parks (not shown on maps) were temporarily closed or had restricted access, including Savanna Portage State Park, Moose Lake State Park, Willard Munger State Trail, Cuyuna Country State Recreation Area, and Soo Line and Blind Lake ATV trails in Aitkin County.

Preliminary damage assessments were done in 13 counties and the Fond du Lac Indian Reservation in the days after the flood. Assessment teams included Federal officials from FEMA, State officials from MHSEM, and local officials. On July 6, 2012, President Obama declared a major disaster existed in northeastern and central Minnesota for the June 14–21, 2012, storm and flood events (Federal Emergency Management Agency, 2012). The disaster declaration brought much needed additional assistance for residents and businesses. This declaration made public assistance requested by the Governor available to State and eligible local governments, and certain private nonprofit organizations on a cost-sharing basis for emergency work and the repair or replacement of facilities damaged by the severe flooding in Aitkin, Carlton, Cass, Cook, Crow Wing, Dakota, Goodhue, Itasca, Kandiyohi, Lake, Meeker, Pine, Rice, St. Louis, and Sibley Counties, as well as the Fond du Lac (not shown), Grand Portage (not shown), and Mille Lacs (not shown) Indian Reservations. This declaration also made Hazard Mitigation Grant Program assistance requested by the Governor available for hazard-mitigation measures statewide.

Summary

During June 19–20, 2012, heavy rainfall, as much as 10 inches locally reported, caused severe flooding across northeastern Minnesota. The floods were exacerbated by wet antecedent conditions from a relatively rainy spring, with May 2012 as one of the wettest Mays on record in Duluth. The June 19–20, 2012, rainfall event set new records in Duluth, including greatest 2-day precipitation with 7.25 inches of rain. The heavy rains fell on three major watersheds: the Mississippi Headwaters; the St. Croix, which drains to the Mississippi River; and Western Lake Superior, which includes the St. Louis River and other tributaries to Lake Superior. Widespread flash and river flooding in northeastern Minnesota that resulted from the heavy rainfall caused more than $100 million dollars in damages. In all, nine counties in northeastern Minnesota were declared Federal disaster areas as a result of the flooding. The June 2012 flooding caused widespread transportation disruptions across Itasca, Aitkin, Carlton, southern Lake, and southern St. Louis Counties. Damages included residences, infrastructure, businesses, public parks, and recreation facilities.

Peak-of-record streamflows were recorded at 13 U.S. Geological Survey streamgages as a result of the heavy rainfall. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities were tabulated for 35 U.S. Geological Survey streamgages. Flood-peak streamflows in June 2012 had annual exceedance probabilities estimated to be less than 0.002 (0.2 percent; recurrence interval greater than 500 years) for five streamgages, and between 0.002 and 0.01 (1 percent; recurrence interval greater than 100 years) for four streamgages. High-water marks were identified and tabulated for the most severely affected communities of Barnum (Moose Horn River), Carlton (Otter Creek), Duluth Heights neighborhood of Duluth (Miller Creek), Fond du Lac neighborhood of Duluth (St. Louis River), Moose Lake (Moose Horn River and Moosehead Lake), and Thomson (Thomson Reservoir outflow near the St. Louis River). Flood-peak inundation maps and water-surface profiles were produced for these six severely affected communities. The inundation maps were constructed in a geographic information system by combining high-water-mark data with high-resolution digital elevation model data. The flood maps and profiles show the extent and depth of flooding through the communities and can be used for flood response and recovery efforts by local, county, State, and Federal agencies.

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Glossary

The following definitions, except where otherwise noted, are from Langbein and Iseri (1960).

annual exceedance probability The probability that a given event magnitude will be exceeded or equaled in any given year. The annual exceedance probability is directly related to the recurrence interval. For example, there is a 1-percent chance that the 100-year peak flow will be exceeded or equaled in any given year. A flood probability of 0.01 has a recurrence interval of 100 years. The recurrence interval corresponding to a particular flood probability is equal to one divided by the flood probability (Holmes and Dinicola, 2010).

cold front A zone separating two air masses, of which the cooler, denser mass is advancing and replacing the warmer mass (National Weather Service, 2009).

continuous-record streamgage A site where data are collected with sufficient frequency to define daily mean values and variations within a day.

crest-stage gage A partial-record streamgage that is nonmechanical, nontelemetered, and intended to record only the peak (crest) stream level since the last site visit.

flood peak The highest value of the stage or discharge attained by a flood; thus, peak stage or peak discharge. "Flood crest" has nearly the same meaning, but because it connotes the top of the flood wave, it is properly used only in referring to stage—thus, "crest stage," but not "crest discharge."

flood profile A graph of elevation of the water surface of a river in flood, plotted as ordinate, against distance, measured in the downstream direction, plotted as abscissa. A flood profile may be drawn to show elevation at a given time or crests during a particular flood.

gage height The water-surface elevation referred to some arbitrary gage datum. Gage height is often used interchangeably with the more general term "stage," although gage height is more appropriate when used with a reading on a gage.

high-water mark The highest stage reached by a flood that has been maintained for a sufficient period to leave evidence on the landscape (Benson and Dalrymple, 1967).

recurrence interval (return period) The average interval of time within which the given flood will be equaled or exceeded once. The recurrence interval is directly related to the flood probability. The recurrence interval corresponding to a particular flood probability is equal to 1 divided by the flood probability. For example, a 100-year recurrence interval has a flood probability of 0.01.

streamflow The discharge in a natural channel. Although the term "discharge" can be applied to the flow of a canal, the word "streamflow" uniquely describes the discharge in a surface stream course.

streamgage A site on a stream, canal, lake, or reservoir where systematic observations of stage, discharge, or other hydrologic data are obtained (U.S. Geological Survey, 2011). In this report, when it is necessary to distinguish between specific types of instrumentation or data used at a streamgage, the following terms are used: "continuous-record streamgage" is used for the sites where continuous-record data are collected, and "crest-stage gage" is used for the sites where partial-record data are collected.

thalweg The area of maximum water velocity within a channel flow (Charlton, 2009).

warm front A transition zone between a mass of warm air and the colder air it is replacing (National Weather Service, 2009).

Appendix 1. High-Water-Mark Descriptions

Table 1–1. High-water-mark descriptions for the mapped communities of Barnum, Carlton, Duluth Heights neighborhood in Duluth, Fond du Lac neighborhood in Duluth, Moose Lake, and Thomson for the floods of June 2012 in northeastern Minnesota.

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, plus or minus (±) 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986).°, degrees; ′, minutes; ″, seconds; --, not available; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark quality	High-water-mark description	High-water-mark identifier	Agency that collected data
				Barnum		
1,099.0	46°30′56.8″	92°41′55.6″	--	Debris line	MR8	USACE St. Paul District
1,097.3	46°30′12.8″	92°41′36.7″	Good	Mud line on building	BARN1	USGS
1,096.3	46°30′16.3″	92°41′32.5″	--	--	MR7	USACE St. Paul District
1,094.4	46°30′8.6″	92°41′29.2″	Poor	Debris line in tree	BARN2	USGS
1,094.0	46°30′8.2″	92°41′28.8″	--	--	MR6	USACE St. Paul District
1,094.0	46°30′4.8″	92°41′28.7″	Good	Mud line in utility shelter	BARN3	USGS
1,088.2	46°29′42.2″	92°41′32.2″	--	--	MR5	USACE St. Paul District
				Carlton		
1,084.1	46°39′47.6″	92°25′54.5″	Good	Mud line on storage container	CARL1	USGS
1,083.4	46°39′46.1″	92°25′45″	Poor	Debris line on fence	CARL2	USGS
1,082.8	46°39′44.7″	92°25′40.1″	Good	Mud line on propane tank	CARL3	USGS
1,082.7	46°39′42.3″	92°25′29.6″	Good	Mud line on Carlton City wastewater treatment plant	CARL4	USGS
1,081.9	46°39′41.9″	92°25′25.6″	Good	Mud line on Carlton City equipment garage	CARL5	USGS
1,081.7	46°39′41.8″	92°25′23.9″	Good	Mud line on house	CARL6	USGS
1,081.7	46°39′42.9″	92°25′22.7″	Good	Mud line on shed	CARL7	USGS
1,081.5	46°39′41.9″	92°25′22.2″	Good	Mud line on house	CARL8	USGS
1,081.9	46°39′50.1″	92°25′45.4″	Good	Mud line on laundry building	CARL9	USGS
1,080.8	46°39′49.5″	92°25′35.8″	Good	Mud line in car shop	CARL10	USGS
1,081.0	46°39′49.5″	92°25′35.8″	Good	Mud line in car shop	CARL11	USGS
1,079.7	46°39′52.4″	92°25′38.6″	Good	Mud line on garage	CARL12	USGS
1,080.0	46°39′54.8″	92°25′37.7″	Good	Mud line on shed	CARL13	USGS
1,079.6	46°39′56.1″	92°25′34.1″	Poor	Mud line on propane tank	CARL14	USGS
1,080.1	46°39′56.8″	92°25′34.6″	Poor	Mud line on house	CARL15	USGS
1,078.2	46°39′57.6″	92°25′31.9″	Poor	As shown by onsite person, line on driveway	CARL16	USGS
1,077.5	46°39′58.2″	92°25′32.1″	Poor	Grass line in trees	CARL17	USGS
1,077.5	46°39′59.9″	92°25′31.7″	Good	Mud line on garage	CARL18	USGS
1,076.9	46°40′0.1″	92°25′32.2″	Fair	Grass line on bushes	CARL19	USGS
				Duluth Heights, Duluth		
1,320.1	46°48′26.2″	92°9′57.8″	Good	Mud line on building	MIL1	City of Duluth; USACE Detroit District
1,320.0	46°48′26″	92°9′53.2″	Poor	Mud line on building	MIL2	City of Duluth; USACE Detroit District
1,320.0	46°48′20.1″	92°9′56.7″	Poor	As shown by onsite person	MIL3	City of Duluth; USACE Detroit District
1,319.9	46°48′18.9″	92°9′49.3″	Fair	Mud line on guard rail	MIL4	City of Duluth; USACE Detroit District
1,320.4	46°48′29.8″	92°10′2.1″	Fair	As shown by onsite person	MIL5	City of Duluth; USACE Detroit District
1,338.8	46°48′45.1″	92°10′25.5″	Fair	As shown by onsite person	MIL6	City of Duluth; USACE Detroit District
1,337.9	46°49′0.4″	92°10′32.4″	Fair	As shown by onsite person	MIL7	City of Duluth; USACE Detroit District
1,340.1	46°49′1.9″	92°10′39.2″	Fair	As shown by onsite person	MIL8	City of Duluth; USACE Detroit District
1,348.3	46°49′17.3″	92°10′35.4″	Fair	Mud line	MIL10	City of Duluth; USACE Detroit District
1,320.4	46°48′30.9″	92°9′48.2″	Good	Mud line in building	MIL11	City of Duluth; USACE Detroit District

Table 1–1. High-water-mark descriptions for the mapped communities of Barnum, Carlton, Duluth Heights neighborhood in Duluth, Fond du Lac neighborhood in Duluth, Moose Lake, and Thomson for the floods of June 2012 in northeastern Minnesota.—Continued

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, plus or minus (±) 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986).°, degrees; ′, minutes; ″, seconds; --, not available; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey]

Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark quality	High-water-mark description	High-water-mark identifier	Agency that collected data
				Fond du Lac, Duluth		
611.6	46°39′40.5″	92°17′4″	Fair	Mud line on power pole next to river	FDL1	USGS
608.5	46°39′39.3″	92°16′58.6″	Poor	Mud line on grass in park	FDL2	USGS
610.2	46°39′35″	92°16′41.4″	Fair	Mud line on red shed	FDL3	USGS
608.5	46°39′35.5″	92°16′38.1″	Fair	Mud line on shed	FDL4	USGS
607.6	46°39′36″	92°16′37.1″	Fair	Grass line on garage	FDL5	USGS
606.8	46°39′33.5″	92°16′37.4″	Fair	Mud line on shed	FDL6	USGS
607.1	46°39′33.8″	92°16′36.7″	Fair	Mud line on shed	FDL7	USGS
609.2	46°39′34.7″	92°16′36.3″	Poor	Grass line on fence	FDL8	USGS
613.5	46°39′40.3″	92°16′26.6″	Poor	Grass line on fence	FDL9	USGS
609.3	46°39′25.4″	92°16′22.1″	Good	Mud line on house	FDL10	USGS
609.5	46°39′16.7″	92°16′22.3″	Good	Seed line on shed	FDL11	USGS
609.3	46°39′16.4″	92°16′22.1″	Fair	Grass line on fence	FDL12	USGS
608.9	46°39′16.1″	92°16′22.1″	Fair	Mud line on house	FDL13	USGS
608.7	46°39′5.6″	92°16′14.4″	Good	Grass line on house	FDL14	USGS
				Moose Lake		
1,052.5	46°27′27.4″	92°45′4.4″	--	--	MR3	USACE St. Paul District
1,048.2	46°27′6.2″	92°44′46.4″	Good	Mud line on paved trail	MOOSE1	USGS
1,049.2	46°27′4.4″	92°44′46.3″	Fair	Mud line on paved trail	MOOSE2	USGS
1,053.3	46°27′23.2″	92°45′24.3″	Poor	Debris line in tree	MOOSE3	USGS
1,052.8	46°27′2.4″	92°45′34.7″	Good	Mud line on building	MOOSE4	USGS
1,052.5	46°26′30″	92°45′40.9″	Good	Debris line on ground	MOOSE5	USGS
1,052.9	46°26′46.2″	92°46′6.9″	Fair	Scratch mark on bridge rail	MOOSE6	USGS
1,052.9	46°26′46.2″	92°46′6.9″	Fair	Scratch mark on bridge rail	MOOSE7	USGS
1,052.1	46°26′45.7″	92°46′7.3″	--	--	MR2	USACE St. Paul District
1,050.8	46°26′50.3″	92°46′17.2″	Good	Mud line on building	MOOSE8	USGS
1,042.9	46°26′38.7″	92°46′34.4″	Poor	Debris line on ground	MOOSE9	USGS
				Thomson		
1,054.9	46°39′49.7″	92°23′27.7″	Good	Mud line on garage	ETHOM1	USGS
1,054.9	46°39′47.9″	92°23′26.8″	Good	Mud line on house	ETHOM2	USGS
1,072.0	46°39′59.9″	92°23′56.6″	Poor	Seed/Grass line on tree	THOM1	USGS
1,071.0	46°39′59.7″	92°23′57.1″	Poor	Seed/Grass line in tree	THOM2	USGS
1,064.9	46°39′58.5″	92°23′59.8″	Poor	Mud line behind studio	THOM3	USGS
1,063.0	46°39′58.4″	92°23′59″	Poor	Mud line on front of studio	THOM4	USGS
1,062.6	46°39′58.1″	92°23′59.8″	Poor	Debris line in grass	THOM5	USGS
1,061.5	46°39′57.4″	92°23′56.5″	Poor	As shown by onsite person, on step next to brick planter	THOM6	USGS
1,050.5	46°39′54.6″	92°23′57.7″	Poor	Debris caught in fence	THOM7	USGS
1,047.2	46°39′52.6″	92°23′57.4″	Poor	Debris line in tree	THOM8	USGS
1,048.6	46°39′52″	92°23′56.6″	Fair	Debris line in power pole	THOM9	USGS
1,046.9	46°39′52.3″	92°24′0.1″	Poor	Debris line at base of stake	THOM10	USGS
1,046.1	46°39′48.9″	92°23′57.6″	Good	Mud line on pump house	THOM11	USGS
1,036.0	46°39′47.4″	92°24′0.4″	Poor	Debris at culvert under bike path	THOM12	USGS
1,041.1	46°39′47.2″	92°23′59.8″	Poor	Debris line in trees	THOM13	USGS

Table 1–2. Descriptions of additional high-water marks for the floods of June 2012 in northeastern Minnesota.

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, ± 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986). °, degrees; ′, minutes; ″, seconds; USACE, U.S. Army Corps of Engineers; --, not available]

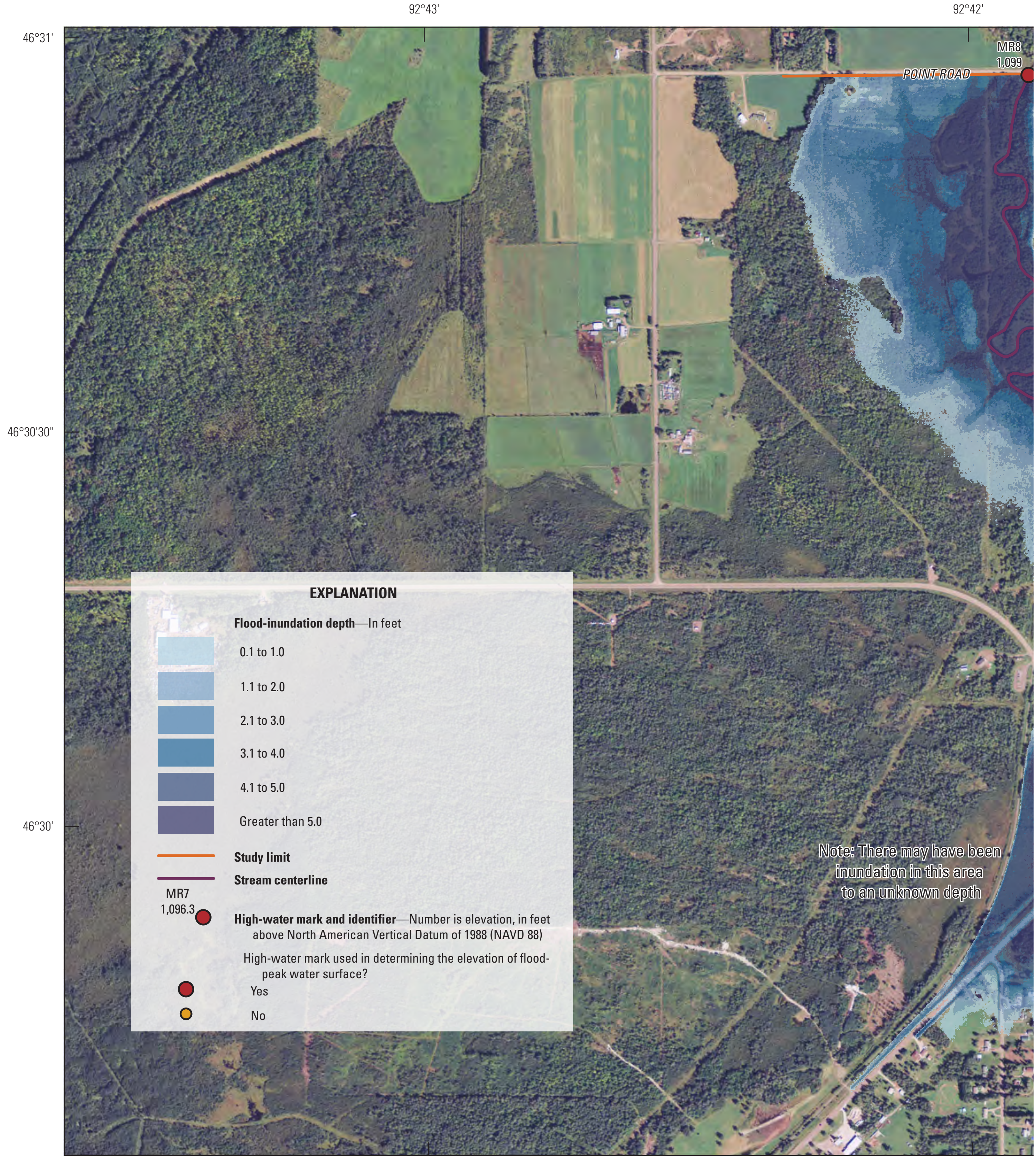
Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark quality	High-water-mark description	High-water-mark identifier	Agency that collected data
				Keene Creek		
616.7	46°43′58.1″	92°10′5.7″	Good	Debris line on fence	KEE1	City of Duluth; USACE Detroit District
615.8	46°43′56.2″	92°10′8.6″	Fair	Debris line at creek	KEE2	City of Duluth; USACE Detroit District
605.9	46°43′58.3″	92°9′34″	Excellent	Debris line on fence	KEE3	City of Duluth; USACE Detroit District
614.8	46°43′59.4″	92°10′16.6″	Good	Mud line on building	KEE5	City of Duluth; USACE Detroit District
622.5	46°44′0.4″	92°10′21.3″	Good	Mud line on structure	KEE6	City of Duluth; USACE Detroit District
624.6	46°44′1.6″	92°10′24.3″	Good	Debris line on fence	KEE7	City of Duluth; USACE Detroit District
654.2	46°44′15.6″	92°10′39.4″	Good	Debris line	KEE9	City of Duluth; USACE Detroit District
651.3	46°44′15.5″	92°10′35.1″	Poor	Mud line on street	KEE10	City of Duluth; USACE Detroit District
				Kettle River		
1,029.8	46°16′6.1″	92°51′41.2″	--	Approximate Coordinates	KR1	USACE St. Paul District
1,036.6	46°18′22.5″	92°51′42.1″	--	Approximate Coordinates	KR2	USACE St. Paul District
1,038.8	46°19′35.6″	92°50′51.8″	--	Approximate Coordinates	KR3	USACE St. Paul District
1,044.5	46°21′38.9″	92°50′33.6″	--	Approximate Coordinates	KR4	USACE St. Paul District
				Kingsbury Creek		
1,237.6	46°44′37.4″	92°13′26.6″	Good	As shown by onsite person	KIN1	City of Duluth; USACE Detroit District
1,248.8	46°44′53.9″	92°13′18.5″	Good	As shown by onsite person	KIN2	City of Duluth; USACE Detroit District
1,248.7	46°44′52.9″	92°13′20.8″	Fair	Mud line on structure. As shown by onsite person	KIN3	City of Duluth; USACE Detroit District
1,238.3	46°44′47.6″	92°13′26.8″	Good	As shown by onsite person	KIN4	City of Duluth; USACE Detroit District
1,238.6	46°44′49.4″	92°13′27″	Good	As shown by onsite person	KIN5	City of Duluth; USACE Detroit District
1,236.5	46°44′44.7″	92°13′28.3″	Poor	As shown by onsite person	KIN6	City of Duluth; USACE Detroit District
1,238.4	46°44′45″	92°13′26.7″	--	--	KIN7	City of Duluth; USACE Detroit District
1,235.2	46°44′40.5″	92°13′42″	Fair	As shown by onsite person	KIN8	City of Duluth; USACE Detroit District
1,236.2	46°44′47.6″	92°13′48.9″	Good	As shown by onsite person	KIN9	City of Duluth; USACE Detroit District
1,247.6	46°44′56.4″	92°14′17.6″	Good	As shown by onsite person	KIN10	City of Duluth; USACE Detroit District
1,230.2	46°44′32.1″	92°13′34.1″	Good	As shown by onsite person	KIN11	City of Duluth; USACE Detroit District
1,229.0	46°44′25.2″	92°13′37.4″	Good	As shown by onsite person	KIN12	City of Duluth; USACE Detroit District
630.9	46°43′31.1″	92°11′32″	Good	As shown by onsite person	KIN13	City of Duluth; USACE Detroit District
631.7	46°43′28.4″	92°11′33.9″	Good	As shown by onsite person	KIN14	City of Duluth; USACE Detroit District
633.0	46°43′27.1″	92°11′27.8″	Good	As shown by onsite person	KIN15	City of Duluth; USACE Detroit District
629.1	46°43′31.3″	92°11′22.7″	Good	As shown by onsite person	KIN16	City of Duluth; USACE Detroit District
				Miller Creek		
652.6	46°45′54.3″	92°7′59.5″	Good	Debris line at bridge	LWMIL14	City of Duluth; USACE Detroit District
652.8	46°45′53.1″	92°8′2.1″	Good	Debris line at bridge	LWMIL15	City of Duluth; USACE Detroit District
644.1	46°45′50.7″	92°7′57″	Good	Mud line on building	LWMIL16	City of Duluth; USACE Detroit District
640.1	46°45′48.1″	92°8′0.5″	Poor	As shown by onsite person	LWMIL17	City of Duluth; USACE Detroit District
639.3	46°45′46.3″	92°7′58.8″	Fair	Mud line on post	LWMIL19	City of Duluth; USACE Detroit District
				Mississippi River		
1,219.8	46°47′31.8″	93°19′36.7″	--	--	MIS1	USACE St. Paul District
1,221.4	46°47′17.8″	93°19′16″	--	--	MIS2	USACE St. Paul District
1,220.0	46°47′11.1″	93°19′28.9″	--	--	MIS3	USACE St. Paul District
1,217.5	46°46′13.8″	93°23′12.4″	--	--	MIS4	USACE St. Paul District
1,214.9	46°43′51.9″	93°26′56.2″	--	--	MIS5	USACE St. Paul District
1,212.8	46°42′39.4″	93°28′42.4″	--	--	MIS6	USACE St. Paul District
1,212.6	46°42′34.9″	93°29′8.3″	--	--	MIS7	USACE St. Paul District

Table 1–2. Descriptions of additional high-water marks for the floods of June 2012 in northeastern Minnesota.—Continued

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, ± 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986). °, degrees; ′, minutes; ″, seconds; USACE, U.S. Army Corps of Engineers; --, not available]

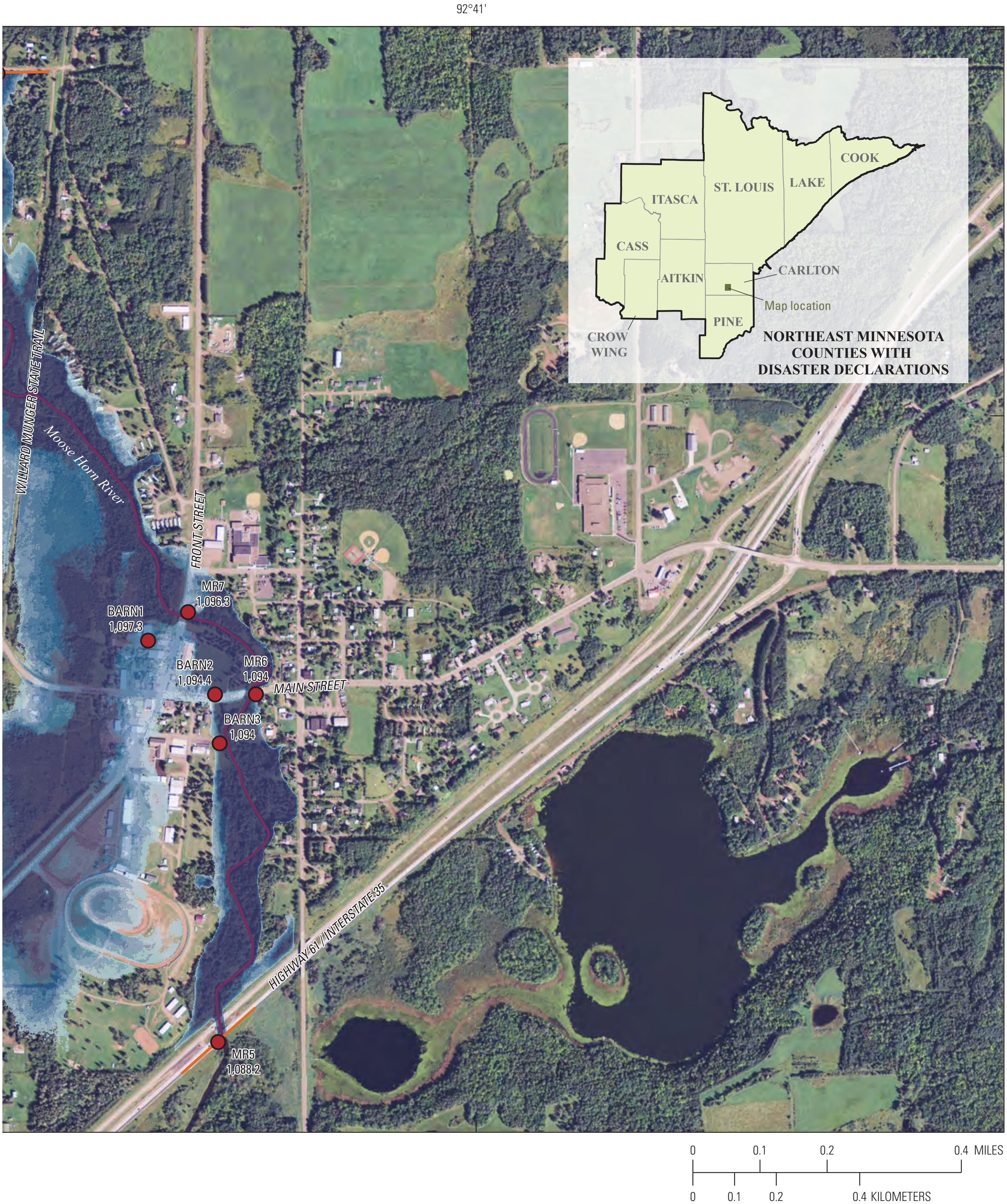
Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark quality	High-water-mark description	High-water-mark identifier	Agency that collected data
				Mississippi River—Continued		
1,210.5	46°41′21.3″	93°32′47″	--	--	MIS8	USACE St. Paul District
1,209.7	46°40′41.5″	93°36′2.8″	--	Overland flow crossing road probably from Willow River	MIS9	USACE St. Paul District
1,209.1	46°40′23.2″	93°36′17.9″	--	--	MIS10	USACE St. Paul District
1,207.7	46°39′6.2″	93°36′44.9″	--	--	MIS11	USACE St. Paul District
1,205.8	46°37′30.5″	93°38′45.5″	--	--	MIS12	USACE St. Paul District
1,203.3	46°35′23.5″	93°39′53.6″	--	--	MIS13	USACE St. Paul District
1,202.1	46°33′42.6″	93°41′47.3″	--	Flood debris / silt line on tree	MIS14	USACE St. Paul District
1,202.1	46°34′46.8″	93°42′25.4″	--	--	MIS15	USACE St. Paul District
1,200.6	46°32′47.8″	93°42′26.5″	--	--	MIS16	USACE St. Paul District
1,201.0	46°32′31.7″	93°42′26.7″	--	--	MIS17	USACE St. Paul District
1,201.2	46°32′28.6″	93°42′22.9″	--	--	MIS18	USACE St. Paul District
1,201.4	46°32′27.2″	93°42′28″	--	--	MIS19	USACE St. Paul District
1,200.1	46°32′51″	93°46′32.6″	--	--	MIS20	USACE St. Paul District
1,199.1	46°34′44.1″	93°47′31.2″	--	Debris line, edge of field, right side of house past electric fence	MIS21	USACE St. Paul District
1,199.3	46°35′3.3″	93°48′6.9″	--	--	MIS22	USACE St. Paul District
1,199.0	46°35′6.6″	93°48′55.9″	--	--	MIS23	USACE St. Paul District
1,197.1	46°34′13.8″	93°52′25.4″	--	--	MIS25	USACE St. Paul District
1,193.0	46°32′38.5″	93°57′20.3″	--	--	MIS26	USACE St. Paul District
				Mississippi River Diversion Channel		
1,202.6	46°35′23.5″	93°39′53.6″	--	--	DC1	USACE St. Paul District
1,203.0	46°35′23.5″	93°39′53.6″	--	--	DC2	USACE St. Paul District
1,202.2	46°35′31″	93°41′12.6″	--	--	DC3	USACE St. Paul District
1,200.1	46°35′34.7″	93°45′38.5″	--	--	DC4	USACE St. Paul District
				Moose Horn River		
1,043.6	46°22′57.5″	92°50′27.9″	--	--	MR1	USACE St. Paul District
1,044.5	46°22′56.8″	92°50′1.7″	--	Approximate coordinates	MR1A	USACE St. Paul District
1,081.7	46°28′37.7″	92°42′47.4″	--	--	MR4	USACE St. Paul District
1,113.4	46°31′10.3″	92°42′34.3″	--	--	MR9	USACE St. Paul District
1,147.7	46°31′9.9″	92°43′43″	--	--	MR10	USACE St. Paul District
				Pine River		
1,028.5	46°15′17.1″	92°51′58.3″	--	Approximate coordinates	PR1	USACE St. Paul District
1,033.4	46°15′34.3″	92°53′37.8″	--	Approximate coordinates	PR2	USACE St. Paul District
1,043.1	46°16′22.1″	92°54′28.1″	--	Approximate coordinates	PR3	USACE St. Paul District
1,071.6	46°18′12.7″	92°54′28.7″	--	Approximate coordinates	PR4	USACE St. Paul District
1,072.7	46°18′36.6″	92°54′28.2″	--	Approximate coordinates. Water on road	PR5	USACE St. Paul District
				Willow River		
1,038.5	46°19′24.9″	92°50′21.5″	--	Approximate coordinates	WR1	USACE St. Paul District

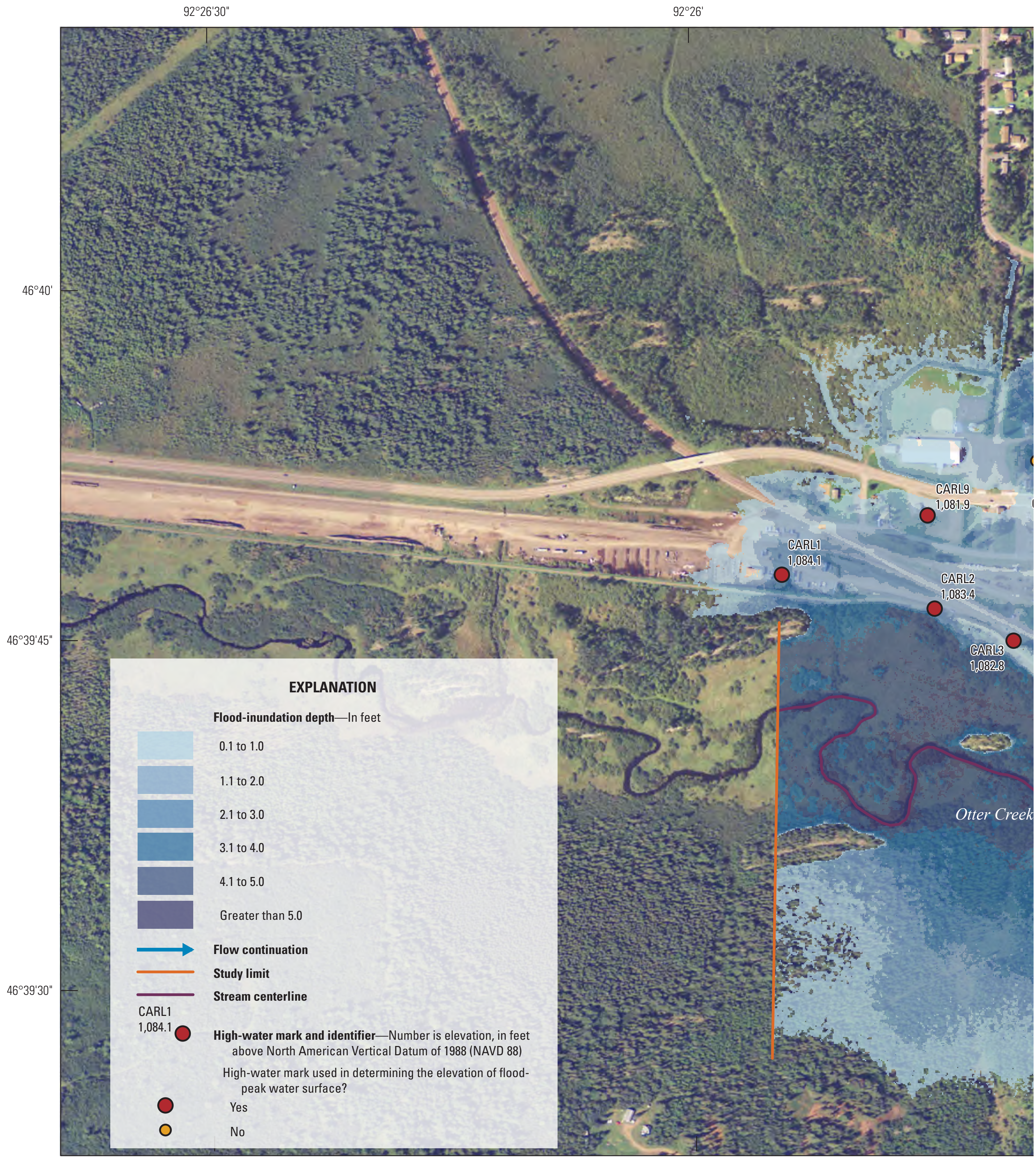
Appendix 2. Flood-Peak Inundation Maps



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

Figure 2–1. Approximate extent and depth of flood-peak inundation, flood of June 2012, for the Moose Horn River at Barnum, Minnesota.

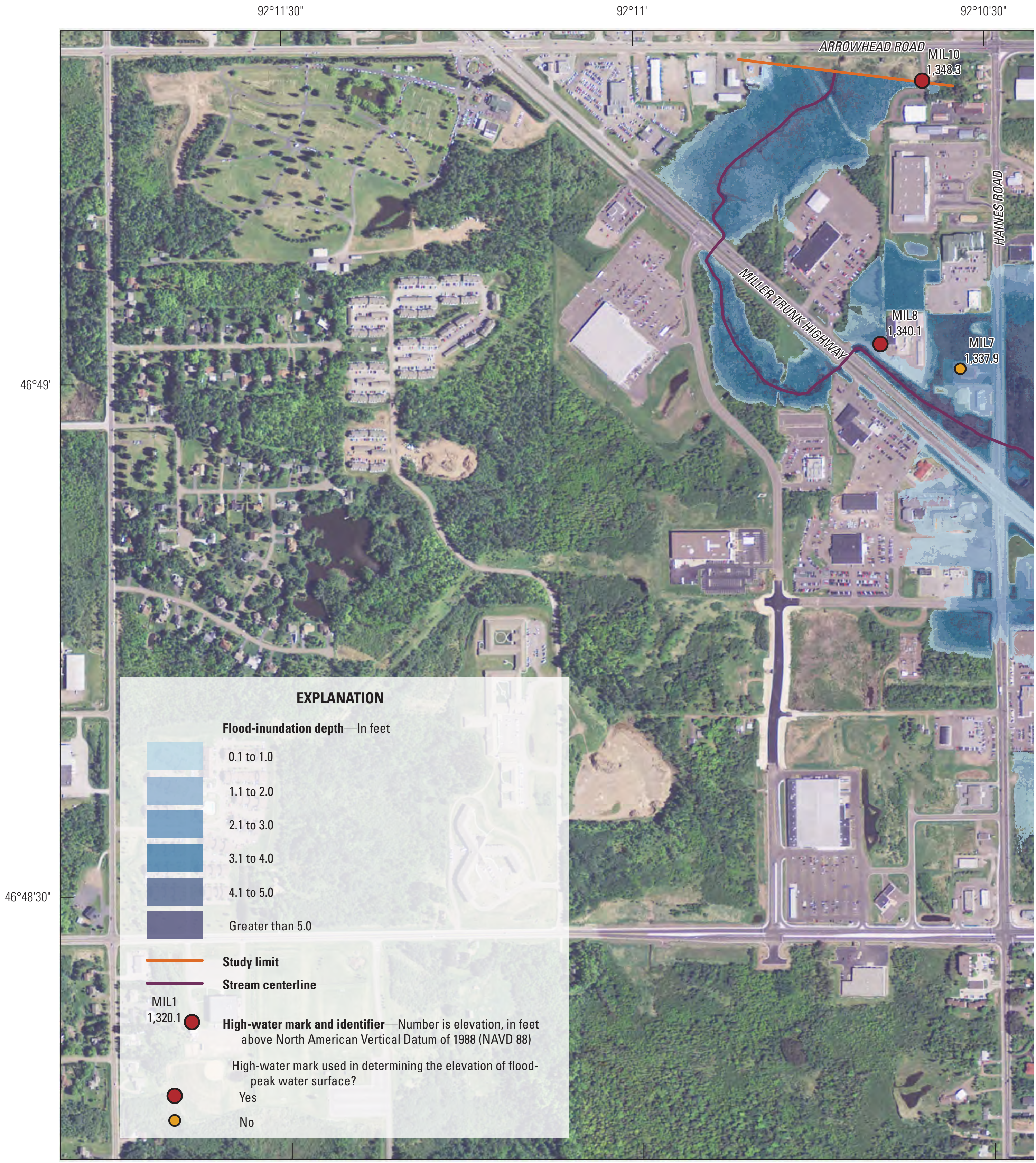

92°41'
COOK
ST. LOUIS
LAKE
ITASCA
CASS
CARLTON
AITKIN
Map location
PINE
CROW WING
NORTHEAST MINNESOTA COUNTIES WITH DISASTER DECLARATIONS
WILLARD MUNGER STATE TRAIL
Moose Horn River
FRONT STREET
MR7 1,096.3
BARN1 1,097.3
BARN2 1,094.4
MR6 1,094
MAIN STREET
BARN3 1,094
HIGHWAY 61 / INTERSTATE 35
MR5 1,088.2
0 0.1 0.2 0.4 MILES
0 0.1 0.2 0.4 KILOMETERS



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

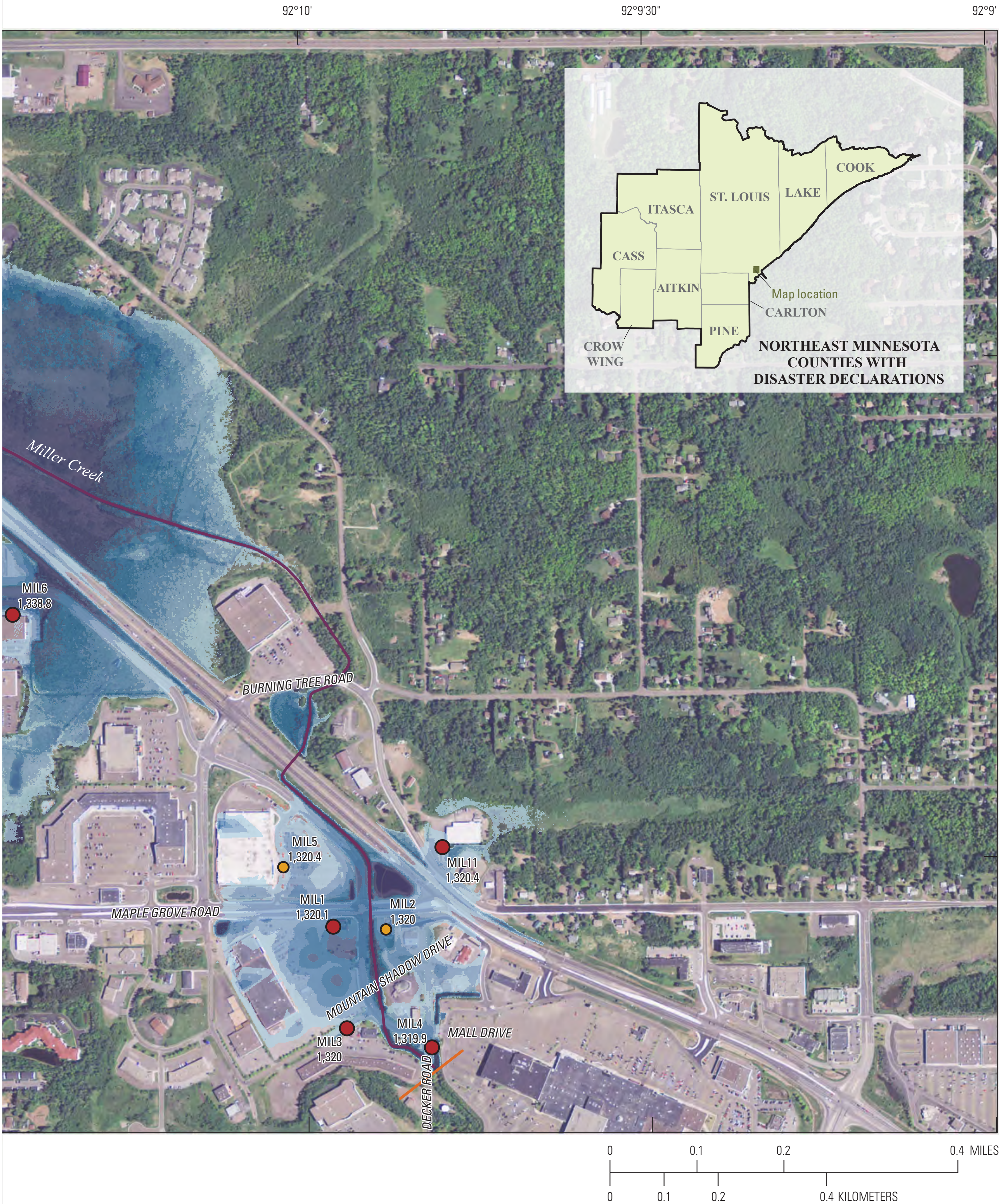
Figure 2–2. Approximate extent and depth of flood-peak inundation, flood of June 2012, for Otter Creek at Carlton, Minnesota.

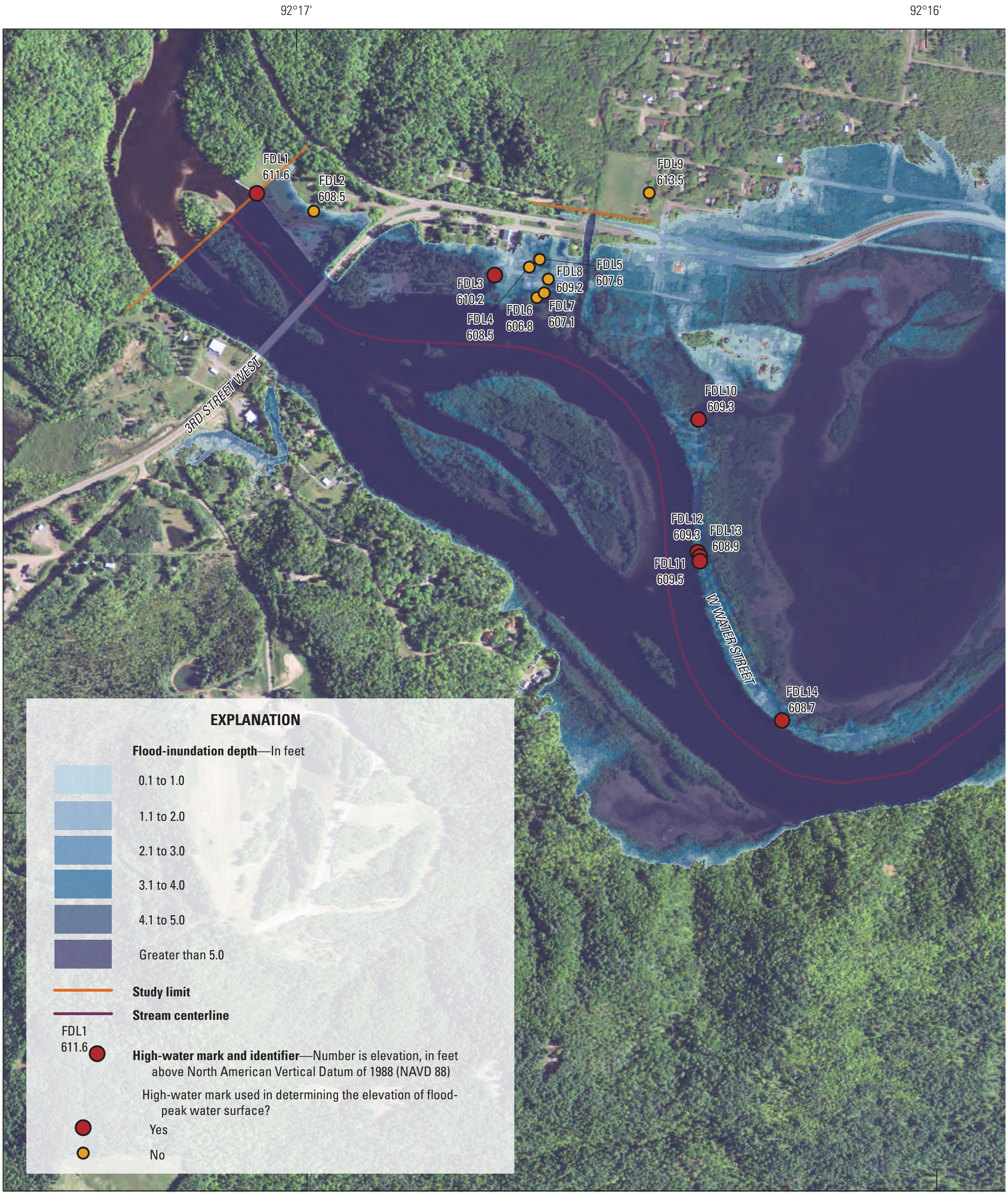

92°25'30"
92°25'
Thomson
Reservoir
CARL19
1,076.9
CARL18
1,077.5
CARL17
1,077.5
CARL15
1,080.1
CARL16
1,078.2
CARL13
1,080
CARL14
1,079.6
CARL12
1,079.7
CARL10
1,080.8
CARL11
1,081
HIGHWAY 210
CARL7
1,081.7
CARL4
1,082.7
CARL5
1,081.9
CARL8
1,081.5
CARL6
1,081.7
COUNTY ROAD 1
WILLARD MUNGER STATE TRAIL
COOK
LAKE
ST. LOUIS
ITASCA
CASS
AITKIN
Map location
CARLTON
PINE
CROW
WING
NORTHEAST MINNESOTA
COUNTIES WITH
DISASTER DECLARATIONS
0
0.1
0.2
0.4 MILES
0
0.1
0.2
0.4 KILOMETERS



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

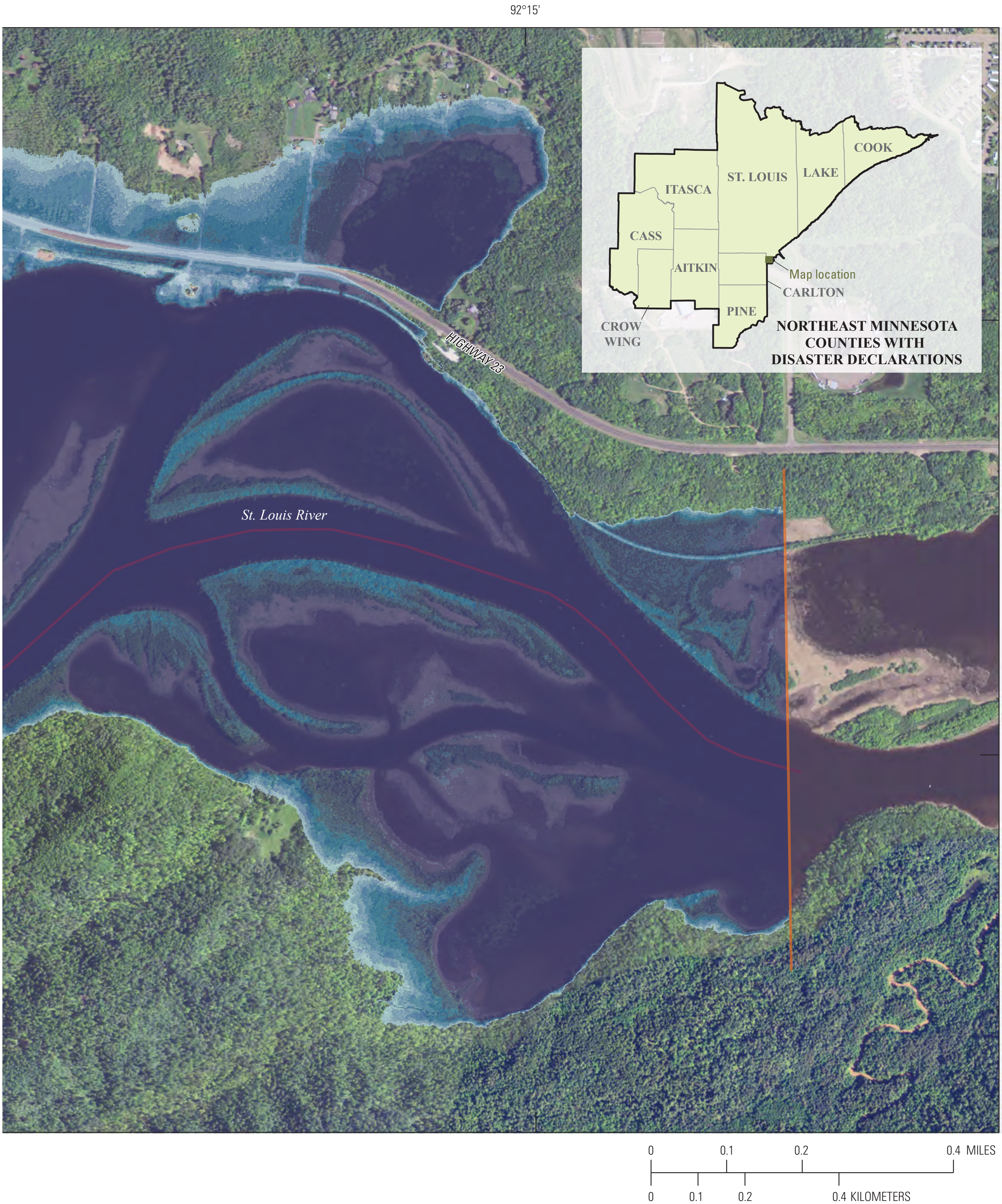
Figure 2–3. Approximate extent and depth of flood-peak inundation, flood of June 2012, for Miller Creek at the Duluth Heights neighborhood, Duluth, Minnesota.

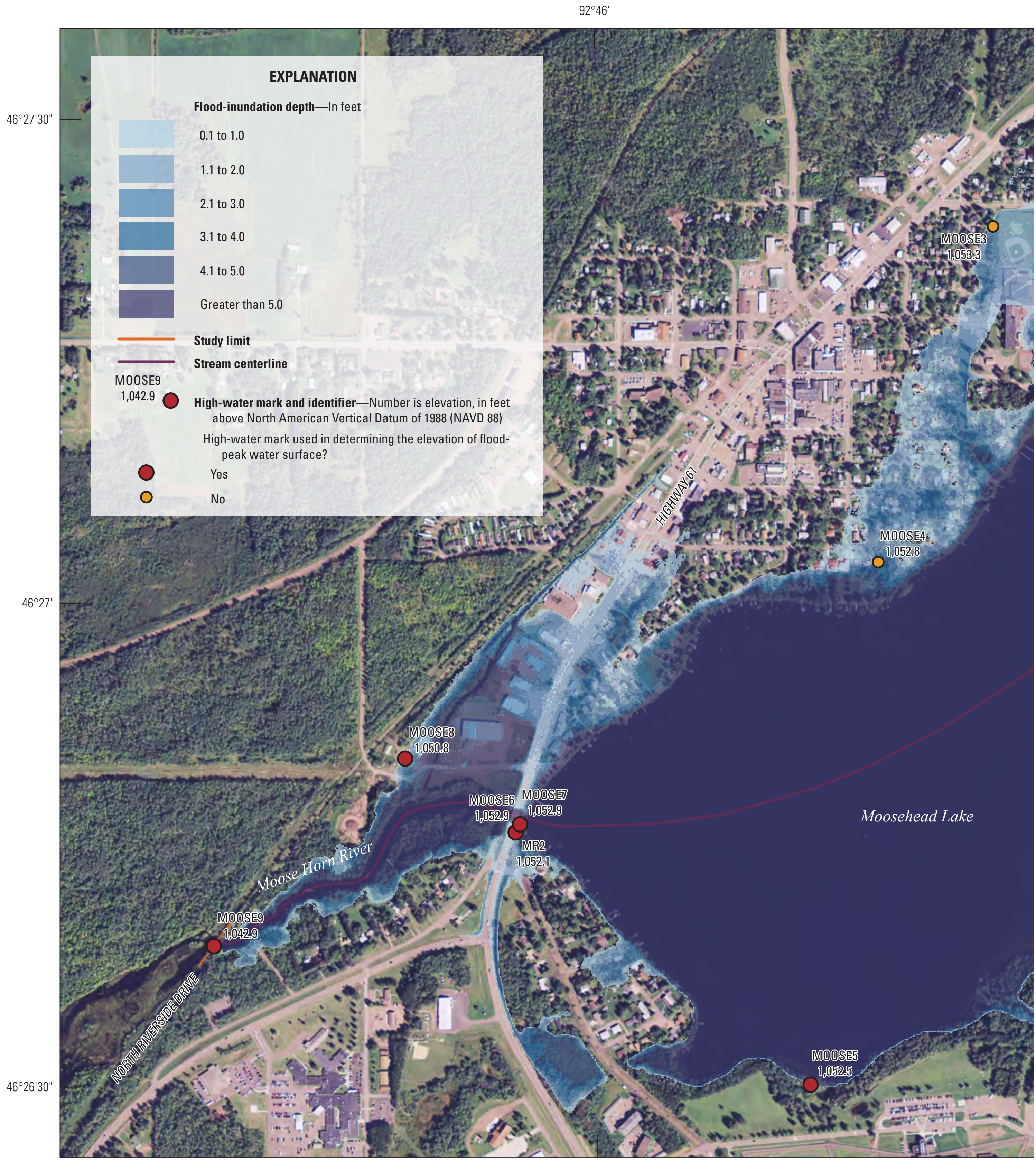

92°10'
92°9'30"
92°9'
COOK
LAKE
ST. LOUIS
ITASCA
CASS
AITKIN
Map location
CARLTON
PINE
CROW
WING
NORTHEAST MINNESOTA
COUNTIES WITH
DISASTER DECLARATIONS
Miller Creek
MIL6
1,338.8
BURNING TREE ROAD
MIL5
1,320.4
MIL11
1,320.4
MIL1
1,320.1
MIL2
1,320
MAPLE GROVE ROAD
MOUNTAIN SHADOW DRIVE
MIL4
1,319.9
MIL3
1,320
MALL DRIVE
DECKER ROAD
0
0.1
0.2
0.4 MILES
0
0.1
0.2
0.4 KILOMETERS



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

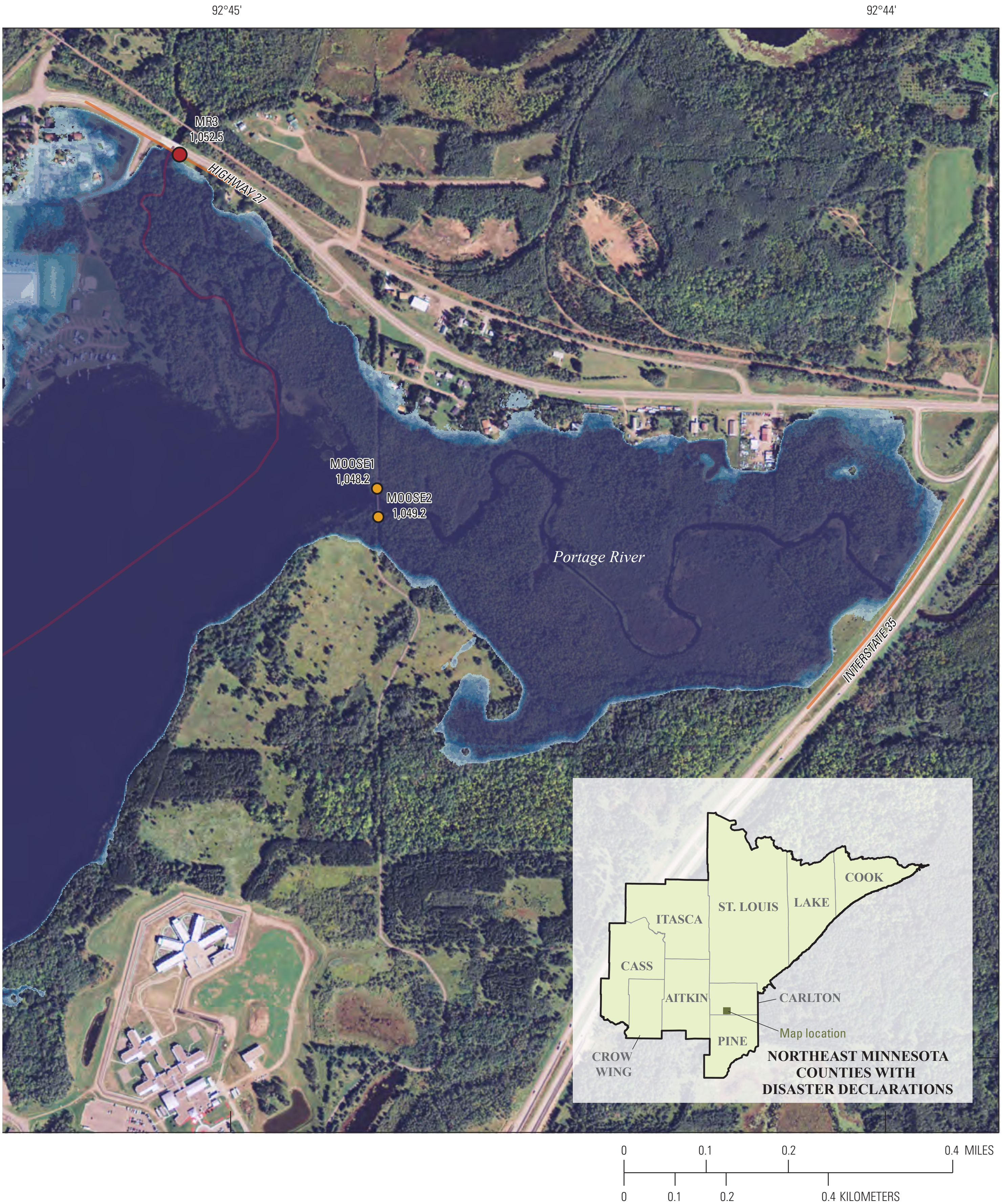
Figure 2–4. Approximate extent and depth of flood-peak inundation, flood of June 2012, for the St. Louis River at the Fond du Lac neighborhood, Duluth, Minnesota.

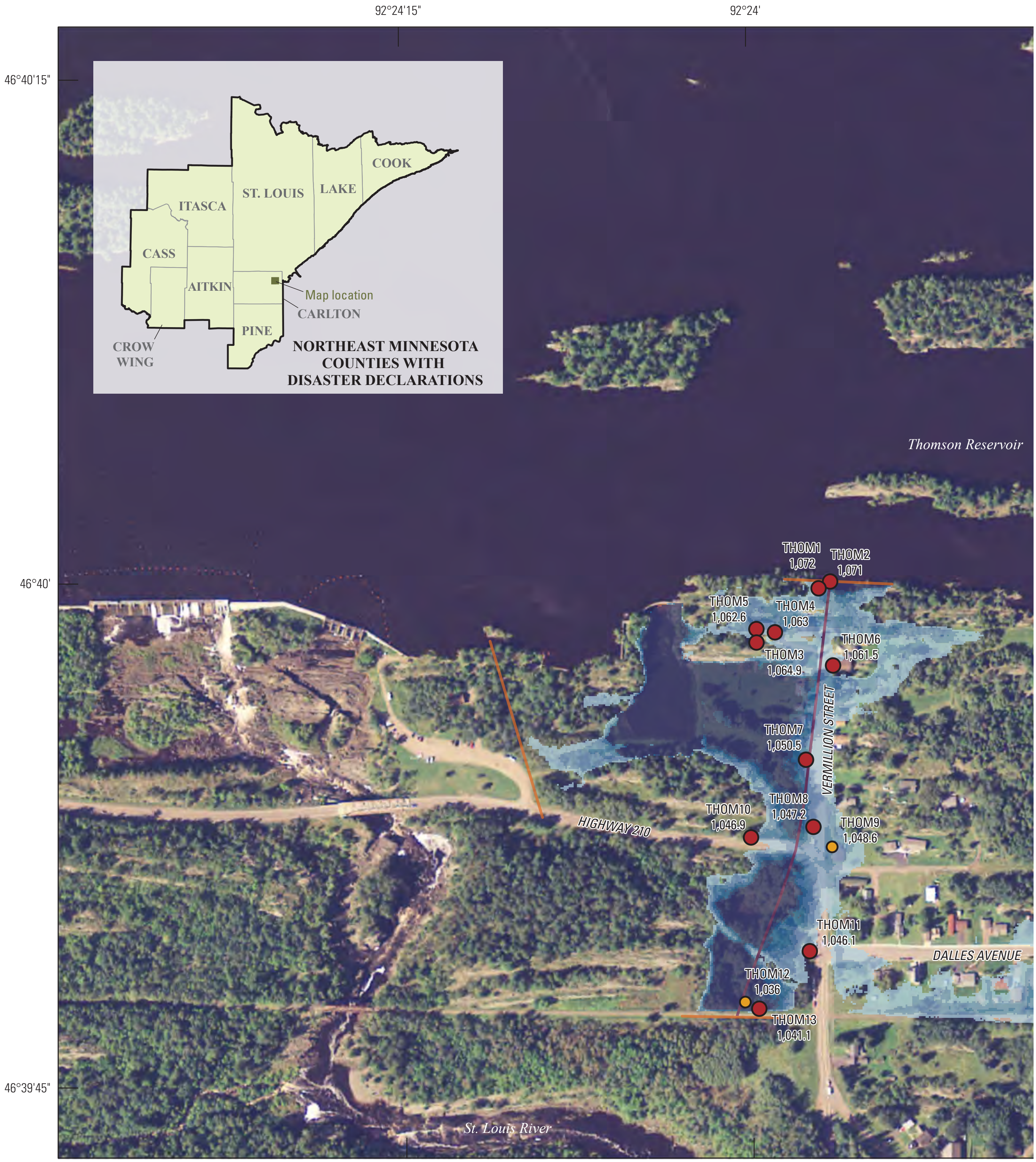

92°15'
HIGHWAY 23
St. Louis River
COOK
LAKE
ST. LOUIS
ITASCA
CASS
AITKIN
Map location
CARLTON
PINE
CROW
WING
NORTHEAST MINNESOTA
COUNTIES WITH
DISASTER DECLARATIONS
0 0.1 0.2 0.4 MILES
0 0.1 0.2 0.4 KILOMETERS



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

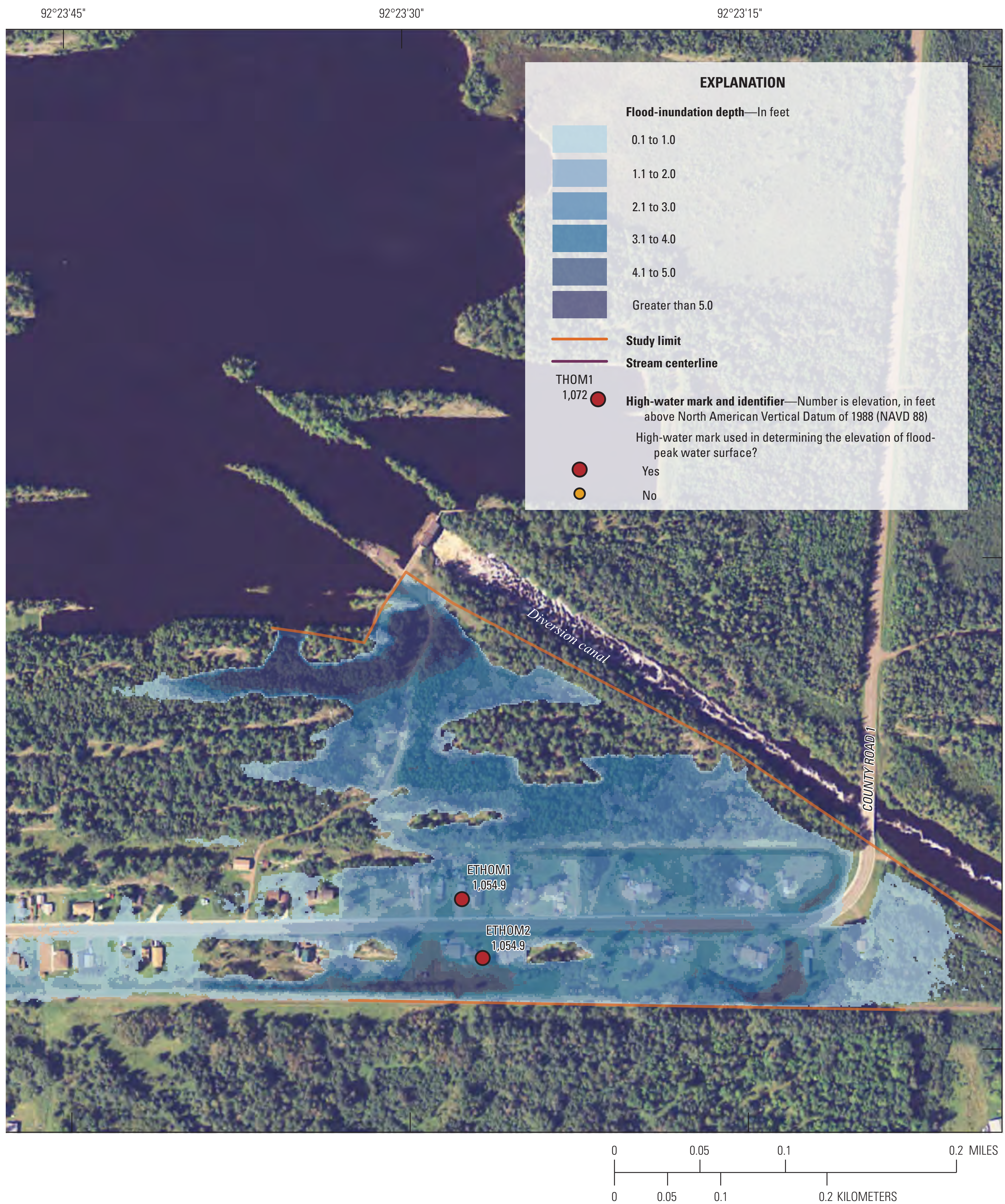
Figure 2–5. Approximate extent and depth of flood-peak inundation, flood of June 2012, for the Moose Horn River and Moosehead Lake at Moose Lake, Minnesota.


92°45'
92°44'
MR3
1,052.5
HIGHWAY 27
MOOSE1
1,048.2
MOOSE2
1,049.2
Portage River
INTERSTATE 35
ITASCA
ST. LOUIS
LAKE
COOK
CASS
AITKIN
CARLTON
Map location
PINE
CROW
WING
NORTHEAST MINNESOTA
COUNTIES WITH
DISASTER DECLARATIONS
0
0.1
0.2
0.4 MILES
0
0.1
0.2
0.4 KILOMETERS



Aerial photograph courtesy of MNGEO, Spatial Data Portal, 2010 National Agriculture Imagery Program, accessed December 2012, at *http://www.mngeo.state.mn.us/chouse/metadata/naip10.html*
Universal Transverse Mercator projection, Zone 15

Figure 2–6. Approximate extent and depth of flood-peak inundation, flood of June 2012, for the Thomson Reservoir outflow near the St. Louis River at Thomson, Minnesota.


92°23'45"
92°23'30"
92°23'15"
EXPLANATION
Flood-inundation depth—In feet
0.1 to 1.0
1.1 to 2.0
2.1 to 3.0
3.1 to 4.0
4.1 to 5.0
Greater than 5.0
Study limit
Stream centerline
THOM1
1,072
High-water mark and identifier—Number is elevation, in feet above North American Vertical Datum of 1988 (NAVD 88)
High-water mark used in determining the elevation of flood-peak water surface?
Yes
No
Diversion canal
COUNTY ROAD 1
ETHOM1
1,054.9
ETHOM2
1,054.9
0 0.05 0.1 0.2 MILES
0 0.05 0.1 0.2 KILOMETERS

Appendix 3. Flood-Peak Water-Surface Profiles

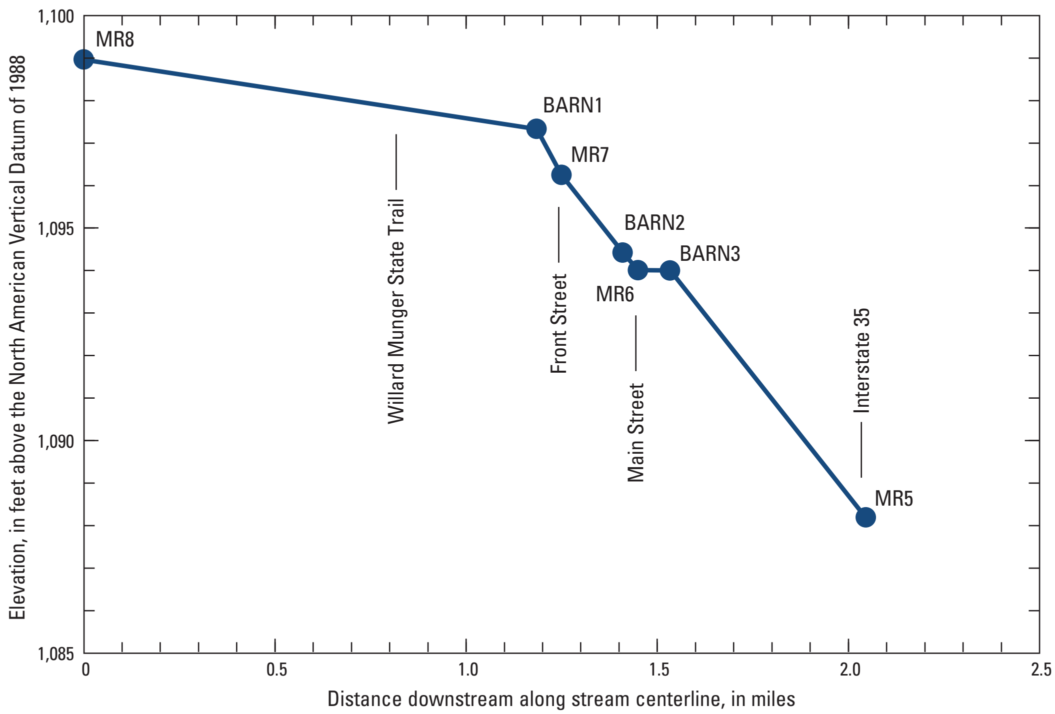


Figure 3–1. Flood-peak water-surface profile with selected high-water marks for the Moose Horn River at Barnum, Minnesota, for the flood of June 2012.

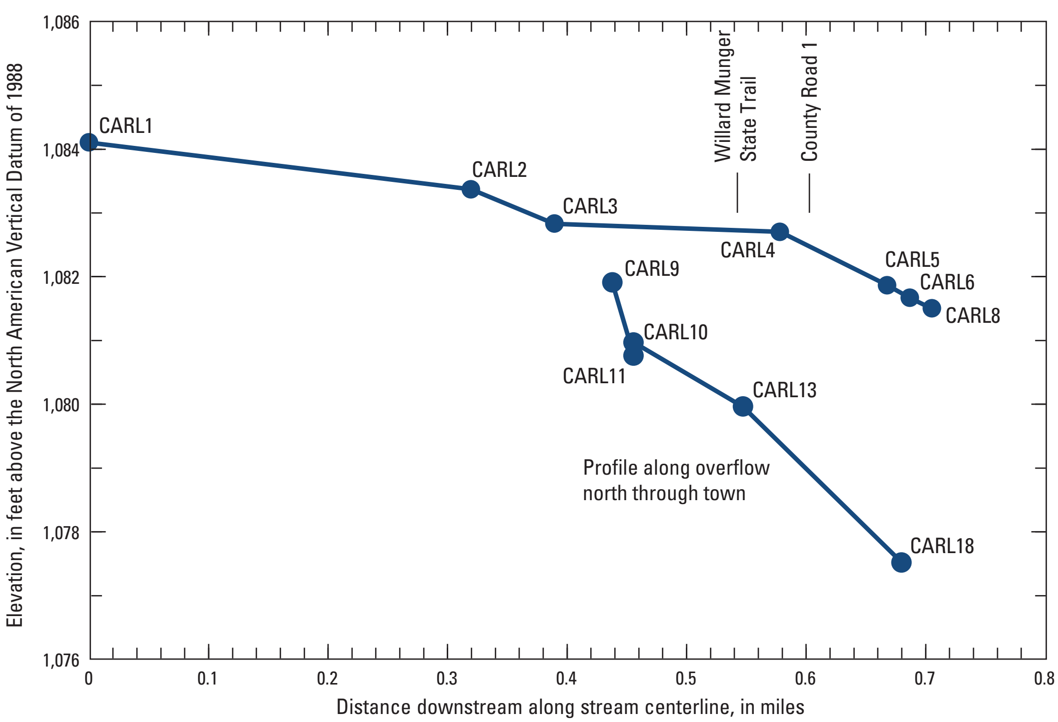


Figure 3–2. Flood-peak water-surface profile with selected high-water marks for Otter Creek at Carlton, Minnesota, for the flood of June 2012.

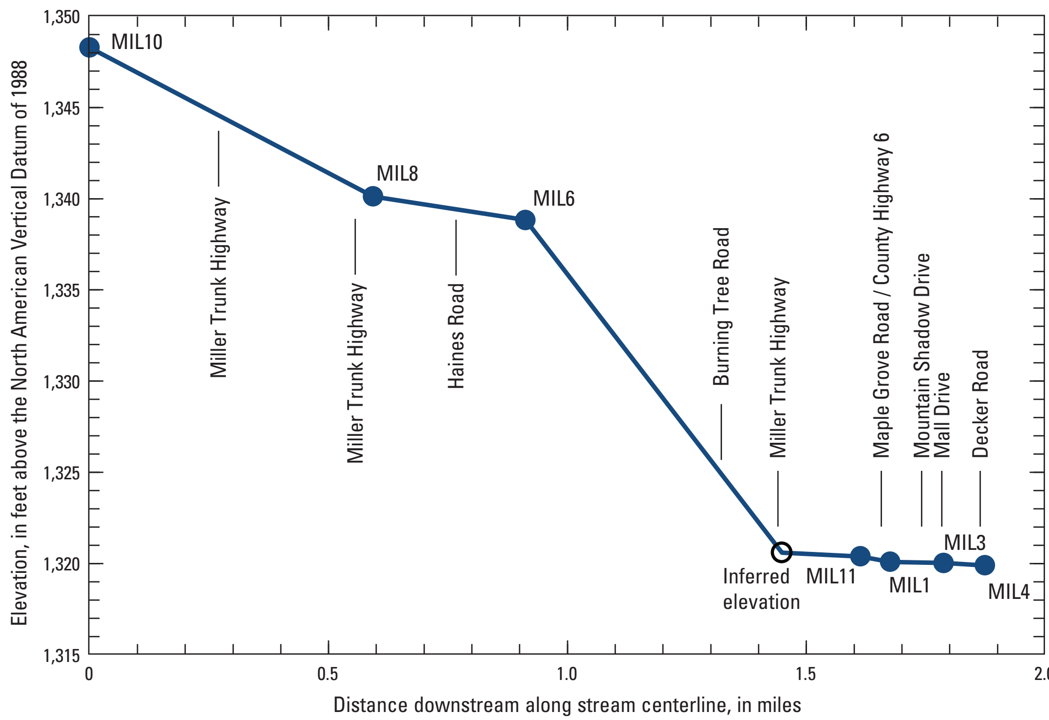


Figure 3–3. Flood-peak water-surface profile with selected high-water marks for Miller Creek at the Duluth Heights neighborhood, Duluth, Minnesota, for the flood of June 2012.

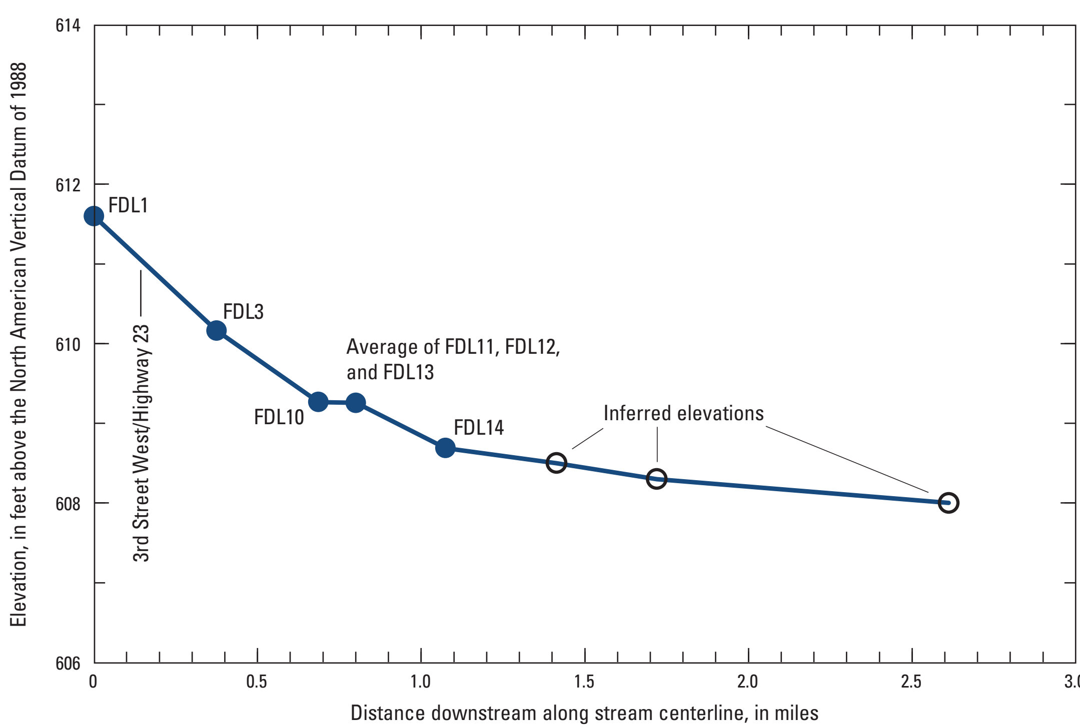


Figure 3–4. Flood-peak water-surface profile with selected high-water marks for the St. Louis River at the Fond du Lac neighborhood, Duluth, Minnesota, for the flood of June 2012.

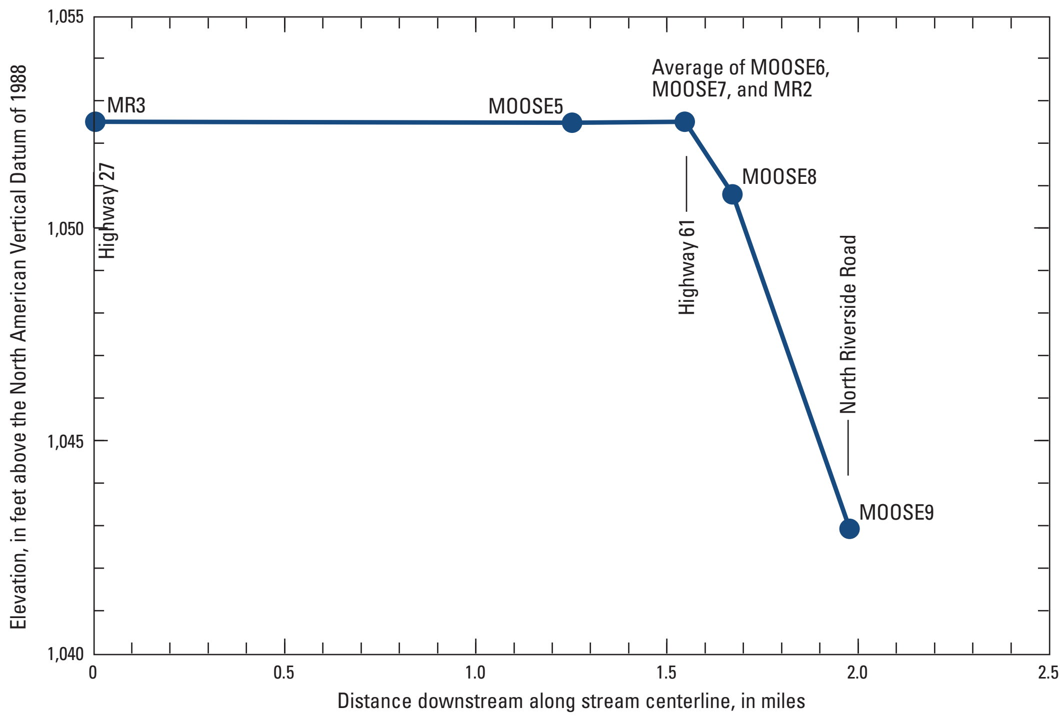


Figure 3–5. Flood-peak water-surface profile with selected high-water marks for the Moose Horn River and Moosehead Lake at Moose Lake, Minnesota, for the flood of June 2012.

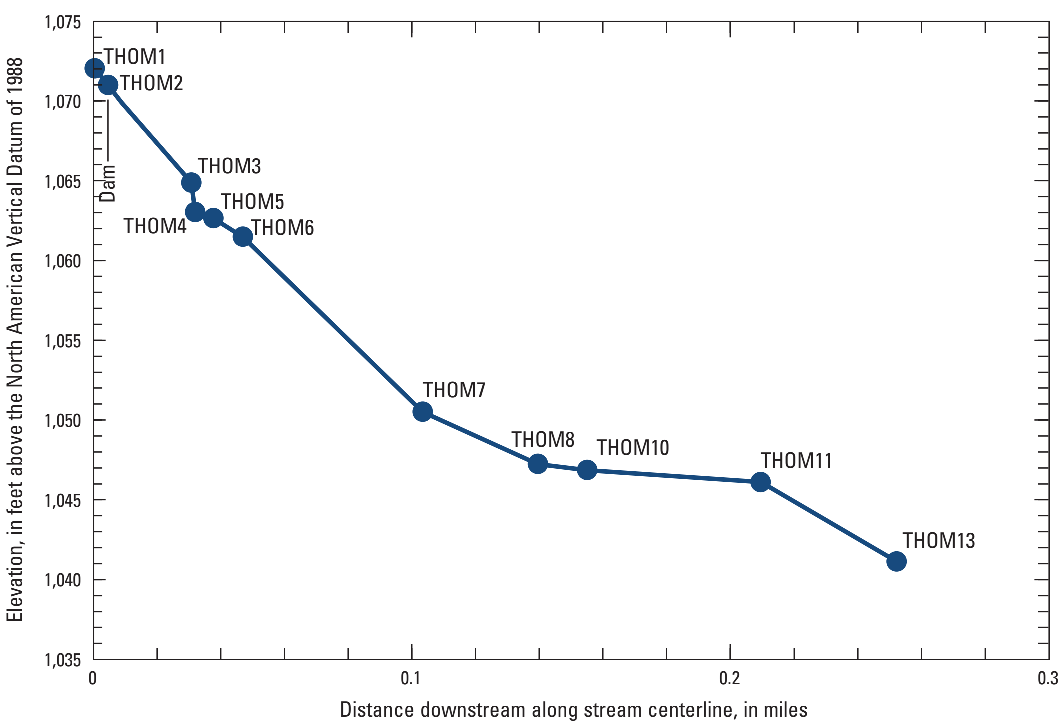


Figure 3–6. Flood-peak water-surface profile with selected high-water marks for the Thomson Reservoir outflow near the St. Louis River at Thomson, Minnesota, for the flood of June 2012.

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Czuba and others—**Floods of June 2012 in Northeastern Minnesota**—Scientific Investigations Report 2012–5283

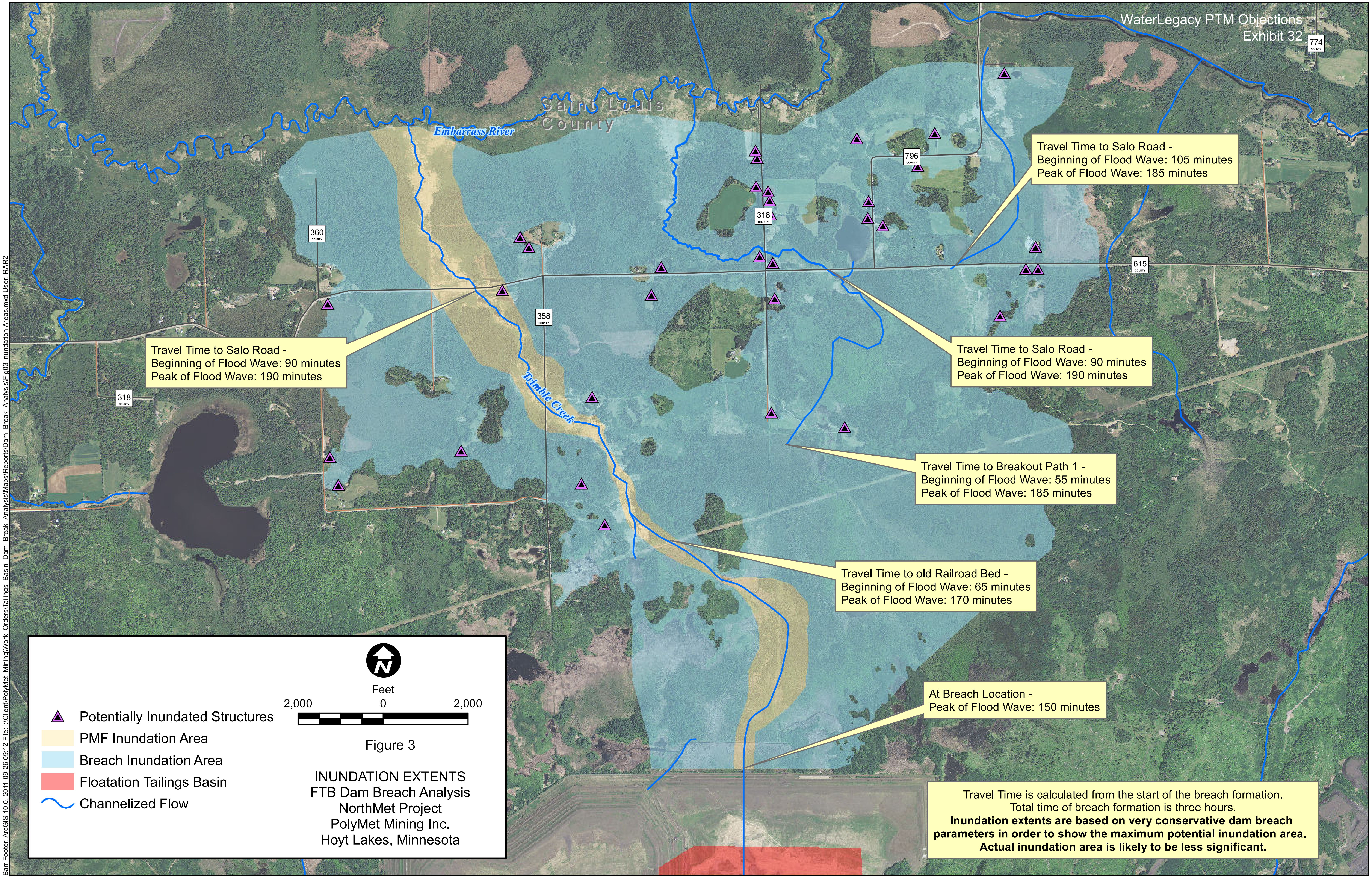

Figure 3

INUNDATION EXTENTS
FTB Dam Breach Analysis
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, Minnesota

Travel Time is calculated from the start of the breach formation.
Total time of breach formation is three hours.
Inundation extents are based on very conservative dam breach parameters in order to show the maximum potential inundation area.
Actual inundation area is likely to be less significant.

Barr Footer: ArcGIS 10.0, 2011-09-26 09:12 File: I:\Client\PolyMet Mining\Work Orders\Tailings Basin Dam Break Analysis\Maps\Reports\Dam Break Analysis\Fig03 Inundation Areas.mxd User: RAR2

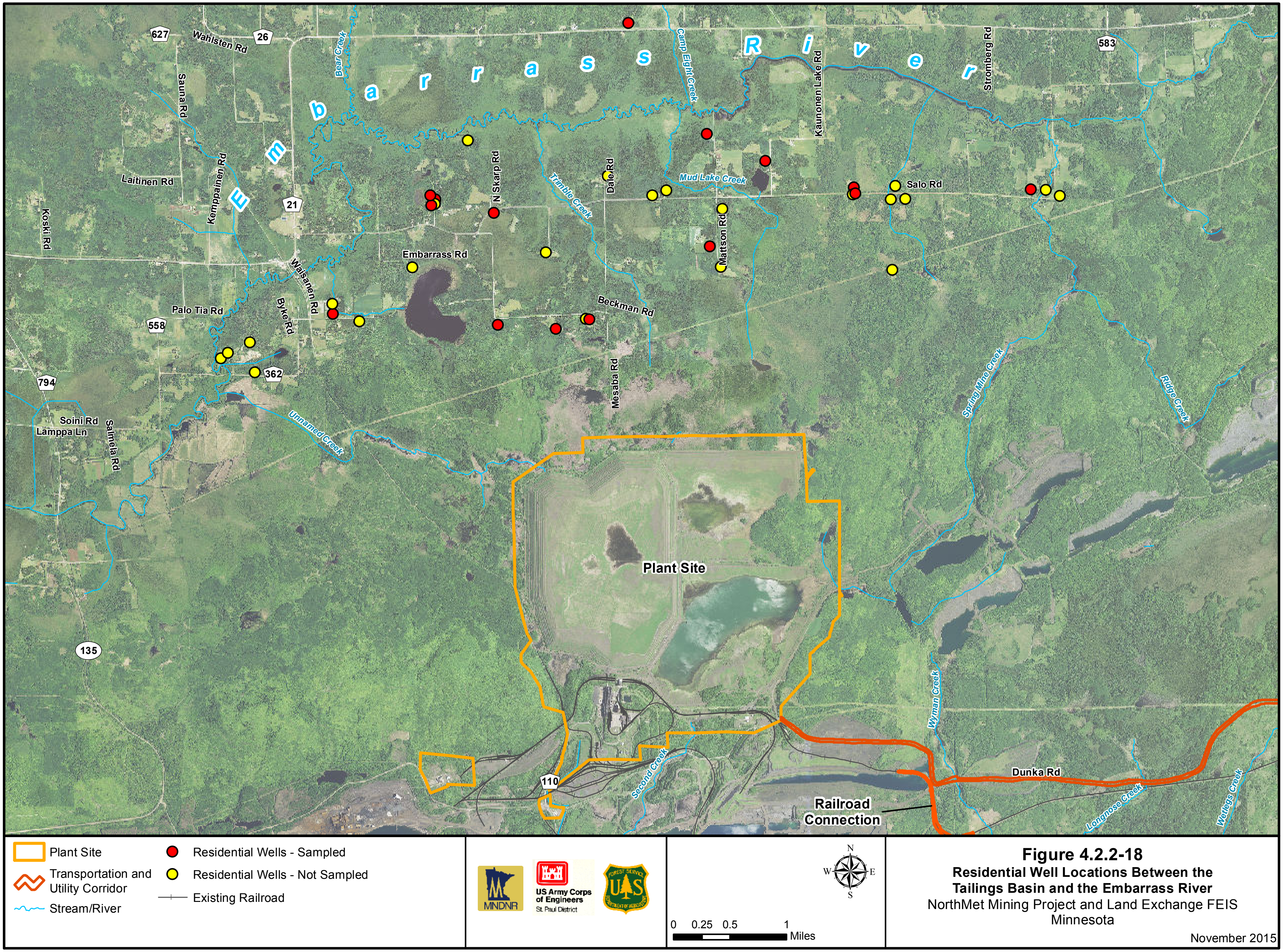

Figure 4.2.2-18
Residential Well Locations Between the Tailings Basin and the Embarrass River
NorthMet Mining Project and Land Exchange FEIS
Minnesota

November 2015

Attachment L

HRF Dam Break Analysis

resourceful. naturally.
engineering and environmental consultants
BARR

Technical Memorandum

To: Poly Met Mining, Inc.
From: Tom Radue, Barr Engineering Co.
Subject: HRF Dam Break Analysis
Date: July 11, 2016
Project: 23690862

Barr Engineering Co. completed a dam break analysis for the Hydrometallurgical Residue Facility (HRF) dams to fulfill dam safety permitting requirements. The HRF dams have been designed to achieve necessary factors of safety (Geotechnical Data Package – Volume II, (Reference (1)), so a dam break is unlikely.

The HRF will be located along the boundary between the Embarrass River watershed and the Partridge River watershed in St. Louis County. The HRF will be three-sided:

- The northern and southwestern dams will be in the Unnamed (Mud Lake) Creek subwatershed of the Embarrass River watershed. The Unnamed (Mud Lake) Creek subwatershed is very sparsely populated. Potential flow paths from the HRF toward Unnamed (Mud Lake) Creek primarily would cross wetland areas interspersed with wooded uplands.
- The southeastern dam will be in the Second Creek subwatershed of the Partridge River watershed. Potential flow paths from the HRF toward Second Creek would be limited by railroad embankments to industrial portions of the PolyMet Plant Site.

Dam break analysis consists of identification of feasible events or a series of events at the HRF that, if not identified and resolved in a timely manner and/or if left unresolved once discovered, could lead to a failure of an HRF dam and the HRF liner system and subsequent release of contained process water or process water and Residue into the environment. For dams associated with liquid containment, such as the HRF dams, failure can be triggered by singular events, or more often, by a series of events. Examples of events that could trigger failure include but are not limited to the following:

- prolonged or massive overtopping of the dam due to uncontrolled discharge into the facility during operations or in combination with inflow from a historic rain event of large magnitude and duration
- uncontrolled or unmitigated seepage through the dam along with internal erosion of the structure of the dam (i.e., migration of soil particles from within the earthen structure of the dam out through the exterior dam face due to particle transport via seepage)
- regional or localized seismic events of sufficient magnitude, acceleration, and duration to damage the foundation or structure of the dam, typically resulting in cracking of the dam or deformation and overtopping
- over–steepening of the dam slopes, resulting in slope instability and failure

- failure of the facility liner system, resulting in uncontrolled seepage and either internal erosion of the dam and/or external sloughing of the dam slope due to saturation of the earthen fill, progressively transitioning to a large scale slope failure
- failure of a nearby piping system resulting in erosion of the body of the dam and potential undermining and failure of the liner system

For a facility with the design characteristics of the HRF it is typical that a chain of events would be required in order to initiate a dam break. Two examples are presented in Table 1.

Table 1 HRF Dam Break Failure Chain Examples

HRF Dam Break	Failure Chain Example 1	Failure Chain Example 2
Event Sequence	1) Facility is operating at the maximum design water elevation	1) A large tear develops through all layers of the double liner system
	2) Return water pipeline becomes inoperable	2) Pond water leaks through the tear and percolates into the HRF dam
	3) Residue transport pipeline discharge to HRF continues	3) The HRF dam structural fill becomes saturated
	4) Historic rain event occurs at the HRF	4) Leakage progresses to the toe of slope and exits with sufficient velocity to cause internal erosion
Failure Mode	Overtopping occurs with overtopping flow concentrated at a single location along the dam crest, eroding a channel through the exterior face of the dam, with erosion progressing back to undercut the liner	Internal erosion evolves to progressive erosion of the dam slope, initiating slope failure and liner failure

Note: The HRF Dam Break failure chains noted above are hypothetical.

Failure chain Example 1 consists of overtopping of the dam; an operations failure concurrent with a historic rain event. It assumes that the return water pipeline is inoperable for an extended period of time and that HRF operations personnel ignore this and the rising water in the facility. This could be accompanied by a significant rainfall that further increases water level and initiates an overtopping event. Such a failure scenario is improbable for the following reasons:

- The facility design and operation accommodates the probable maximum precipitation. Per Hydrometeorological Report number 51 (HMR 51), Probable Maximum Precipitation Estimates, United States East of the 105th Meridian, the 72-hour Probable Maximum Precipitation (PMP) event at the HRF is on the order of 32 inches. The freeboard to be maintained during HRF operations will be a minimum of 36 inches from the top of HRF liner system, with additional freeboard provided by the crest of dam liner system cover materials.

The failure would require prolonged mismanagement on the part of multiple facility operations personnel. This is improbable for the following reasons:

- Daily HRF inspections and water level monitoring would identify a notable change in the rate of water level rise in the HRF.
- The water returned to the Hydrometallurgical Plant is put back into the process to facilitate ongoing operations and to minimize water consumption. A long-term shutdown of the water return line would impact plant operations.

- The water is returned to the process to recover the metals in solution and increase metal recovery. A long-term shutdown of the water return line would impact the metal recovery.
- Under routine operating conditions but absent return water, several months would be required to discharge sufficient water into the HRF to initiate overtopping. At the projected HRF inflow rate of 218 gallons/minute, approximately 55 days would be required to raise the pond level a single foot; sufficient time to identify and resolve any operations issues.

Failure chain Example 2 consists of development of a large tear through all layers of the double liner system. For the HRF as proposed, with its relatively flat embankment slopes and intermediate benches to prevent development of strain in the liner system, the most probable initiation point of a tear would be at the base of the facility. This would be the result of large scale localized differential settlement of the HRF foundation materials. Settlement of sufficiently large scale would be required to induce strain in the liner system in excess of the liner system's strain tolerance. Another potential source of tears in the liner system would be from construction activities during initial liner construction. However, both liner tear scenarios are improbable and hence the overall failure scenario is improbable for the following reasons:

- The HRF foundation materials will be pre-loaded to induce settlement and to eliminate the potential for future large scale differential settlement, thereby minimizing strain in the liner system.
- The Linear Low Density Polyethylene (LLDPE) Geomembrane and the Geosynthetic Clay Liner (GCL) hydraulic barriers of the HRF liner system are selected for strain tolerance well in excess of the strain estimated to occur after pre-loading.
- The HRF embankments will be built using compacted structural fill that will not be subject to large scale differential settlement.
- Leak location surveys will be implemented on each geomembrane layer of the HRF liner system following completion of primary construction activities but prior to placing the HRF into service. Leak location surveys are effective at identifying holes in geomembrane liner systems.
- Larger holes and tears are readily detected by visual review of liner quality without the need for leak location surveys.
- Seam strength and integrity testing will be conducted on all seams of geomembrane panels and at geomembrane patch locations during construction.
- The volume of water required to fill all the pores in the embankment is large (millions of gallons) and its loss from the system should be noticed by operations.

- The material proposed to construct the HRF embankments is course, angular material not readily susceptible to piping failures/internal erosion.
- Seepage of significant quantity would be detected in the HRF leakage collection system and/or at the toe of slope of the facility, in the facility groundwater monitoring wells, and/or in the piezometers used for embankment performance monitoring. This data would serve as an early warning that leakage is occurring out of the HRF and mitigative measures could be implemented.

The failure scenarios described previously are two scenarios that, while theoretically possible, have a low probability of occurrence for the reasons summarized above. Further, the HRF dams will be constructed using compacted structural fill overlain by a multi-layer geosynthetic liner system. This type of liner system, when constructed by a qualified contractor using industry-standard quality control techniques, is highly effective at minimizing leakage. Finally, freeboard to be maintained within the HRF will accommodate addition of water and Residue over a period of months prior the threat of overtopping.

Additional hydrologic and hydraulic modeling to detail the extent of inundation from an HRF dam break is not warranted because no plausible HRF dam failure scenarios have been identified.

References

1. **Poly Met Mining Inc.** NorthMet Project Geotechnical Data Package Vol 1 - Flotation Tailings Basin (v8). May 2017.

The RISK, PUBLIC LIABILITY, & ECONOMICS of TAILINGS STORAGE FACILITY FAILURES

Lindsay Newland Bowker[1] & David M. Chambers[2]
July 21, 2015

1. Introduction

Prior works interpreting the history of Tailings Storage Facility (TSF) failures, 1910-2010, have concluded that the lower numbers of failures and incidents in the two most recent decades evidence the success of modern mining regulation, improved industry practices and modern technology. When examined more closely the 100 years of TSF failures shows an emerging and pronounced trend since 1960 toward a higher incidence of "Serious"[3] and "Very Serious"[4] failures. That is, the consequence of loss is becoming increasingly greater.

In a keynote address at a 2011 tailings conference Dr. A. Mac G Robertson described this trend and its implications going forward as elevating risk potential by a factor of 20 every 1/3 century. His address called a "red flag" on the current "Mining Metric" which results in ever larger and higher TSFs (Robertson 2011).

Risk potential has increased by a factor of 20 every 1/3 century. (Robertson 2011)

The Mining Metric creating this exponentially increasing consequence in the event of a tailings dam failure, is driven by continuously lower grades in identified resources and continuously falling real prices of most metals. The costs to excavate more material for a ton of end product at a lower price has been made possible through technology improvements in milling and concentration processes, bulk mining and economies of scale. There have been some new technologies e.g. dry stack and paste tailings and the more prevalent use of center line over upstream dam designs which offer the potential for lower consequence in the event of failure, and perhaps a lower overall risk of failure. However, many of the same features of modern mining that create economic feasibility in lower grades of ore also pose greater challenges for the management of mine waste and waste water. One of the manifestations of these challenges overall is a greater frequency of Very Serious tailings dam failures with significant levels of social and economic consequence, sometimes non remediable.

The modern "Mining Metric" is well mapped: higher mine production necessitated by lower grades of ore, a century of declining prices offset by declining costs per ton. The metric is to continuously develop the resource through economies of scale, larger and deeper footprints, more efficient operations, bigger and better bulk mining technology.

49% (33/67) of all recorded Serious and Very Serious failures from 1940-2010 have occurred since 1990. Of all 52[5] recorded incidents cited, 1990-2010, 17 (33%) were Serious failures, i.e. large enough to cause significant impacts or involved loss of life. Another 16 (31%), were Very Serious failures, i.e. catastrophic dam failures that released more than 1

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3 We defined Serious failures as having a release of greater than 100,000 cubic meters and/or loss of life.

4 We defined Very Serious failures as having a release of at least 1 million cubic meters, and/or a release that travelled 20 Km or more, and/or multiple deaths (generally ≥ 20).

5 Our study included authoritatively documented TSF failures that were not in the WISE or ICOLD inventories. See Appendix 1, TSF Failure Data Table, for a complete list of TSF incidents & failures included in our study and the basis on which they were classified.

million cubic meters of tailings and in some instances resulted in multiple loss of life. 63% of all incidents and failures since 1990 were Serious or Very Serious. The total costs for just 7 of these 16 large failures was $3.8 billion, at an average cost of $543 million per failure (See Appendix 3). These losses, according to dam committee reports and government accounts are almost all the result of failure to follow accepted practice. These failures are a direct result of the increasing prevalence of TSF's with greater than a 5 million cubic meter total capacity necessitated by lower grades of ore and the higher volumes of ore production required to attain or expand a given tonnage of finished product. We project 11 Very Serious failures 2010-2020 at total unfunded unfundable public cost of $6 billion. We estimate an additional $1 billion for 12 Serious failures this decade. These losses are uninsurable. Very few miners can simply absorb a loss at this scale without risking bankruptcy and permanent closure of a resource that has not yet been "mined out". There is no organized industry attempt to pool these losses in the context of a risk management loss prevention program, and no political jurisdiction issuing permits is large enough to prefund a low frequency high consequence loss of this scale. The inevitable result is either government pays or the damages go unremediated.

Much of our data on cost of large scale failures was sourced from court cases or proceedings where government sought unsuccessfully to recover what had been spent on remediation, compensation for damages or assigned as value for actual socio economic and natural resources loss. Shielded via wholly owned subsidiaries who can legally declare bankruptcy when liabilities exceed assets of the subsidiary (not the parent), the parent companies paid little or nothing toward most of these large losses. In countries founded on the common law tradition that all are responsible for the consequence of their actions, this gap between outcome and expectation for the most serious local impacts violates the terms and conditions of a "social license to operate" and fails to meet a standard of "polluter pays".

Miners Must Move Forward or Perish (Jones 2014)

As we have seen with Mt. Polley, very large releases do not just occur at very large mines. In comparison to the scale envisioned by mines like Pebble or KSM, the Mt. Polley TSF was relatively small, only about 35 meters high at failure with a total capacity of about 74 million cubic meters (Independent Panel 2015). In fact this is the pattern we see on close examination of Very Serious and Serious failures; older TSFs with smaller footprints are pushed to unplanned heights to accommodate additional production that was not anticipated when the tailings dams were originally designed and the permits originally issued.. Capital markets and investors don't finance clean ups. They finance production that is profitable. Smaller companies operate on tighter margins within the same overall metric affecting all miners but are less able to take advantage of and finance optimizations or achieve economies of scale that will keep production costs low enough to maintain a specific mine site as economically feasible.

Our sense of the data and the case histories we have looked to for a deeper understanding of the data is that "mining economics" plays a significant role in TSF failures and that it is important in permitting and in the regulatory process to look beyond the "mechanisms of failure" to the fundamental financials of the miner, the mine, and mega trends that shape decisions and realities at the individual mine.

Our sense of the data, and the case histories we have looked to for a deeper understanding of the data, is that "mining economics" plays a significant role in TSF failures. It is important in permitting, and in the checks and balances built into the regulatory process over the life of a TSF, to look beyond "mechanisms of failure" to the fundamental financials of the miner, the mine, and mega trends that shape decisions and realities at the level of miner and individual mine.

Taking our study of the relationship between "mining economics" and TSF failures 1910-2010 into account, it is our expectation that large failures in the near term (through 2020) will continue to come from operating mines under ownership of smaller miners first commissioned from the late 60's to the early or late 80's. These smaller older mines are producing within the Mining Metric of lower grades and now steeply rising production costs against the continuous possibility of a sharp adverse price swing but with much less capital, as compared with larger mines, to buffer contingencies or provide required levels of stewardship for TSFs from design through closure. For a mega mine like the 100 year old Bingham Canyon mine it was possible to respond to an identified threat of failure and the growing environmental problems of age. It is not clear how smaller old mines will find the funds to identify or respond in a timely fashion to threats at their facilities, or whether regulatory structures now in place will serve well enough to identify such "at risk" facilities.

If they are identified in time, it is not clear how smaller miners skating on thin balance sheets will finance the closure or improvements at TSFs and carve out the funds for new TSFs where necessary. Larger mining companies, however, are better positioned financially to manage and mitigate these threats.

This study anticipates the future trend of Serious and Very Serious TSF failures over the next decade, through 2020, and estimates the total public economic consequence of those failures, which are presently unfunded and un-fundable. We borrow the applicable elements of "loss development" in insurance rate making utilizing 100 years of data on loss and consequence and on the production levels of the mining metric producing TSF waste volumes to project an expected number of failures and an average expected loss per failure from which global estimates of expected public loss can be reasonably estimated.

Having something more like "actuarial data" to refer to is important in understanding the potential magnitude of loss from an individual dam or a permitting districts portfolio of dams and TSFs. With such low frequency high severity losses we can never assign risk to an individual TSF based on its design and receiving environment parameters. Unless it has an identified flaw that puts it at near certain risk of imminent failure, we can't say whether a given dam "will" fail. We can only say what the consequence would be in economic terms if it failed.

Satellite imagery has lead us to the realization that tailings facilities are probably the largest man-made structures on earth. Their safety, for the protection of life, the environment and property is an essential need in today's mining operations. These factors, and the relatively poor safety record revealed by the numbers of failures in tailings dams have led to an increasing awareness of the need for enhanced safety provisions in the design and operation of tailings dams. (ICOLD 2001)

2. Increasing Consequence of Failures

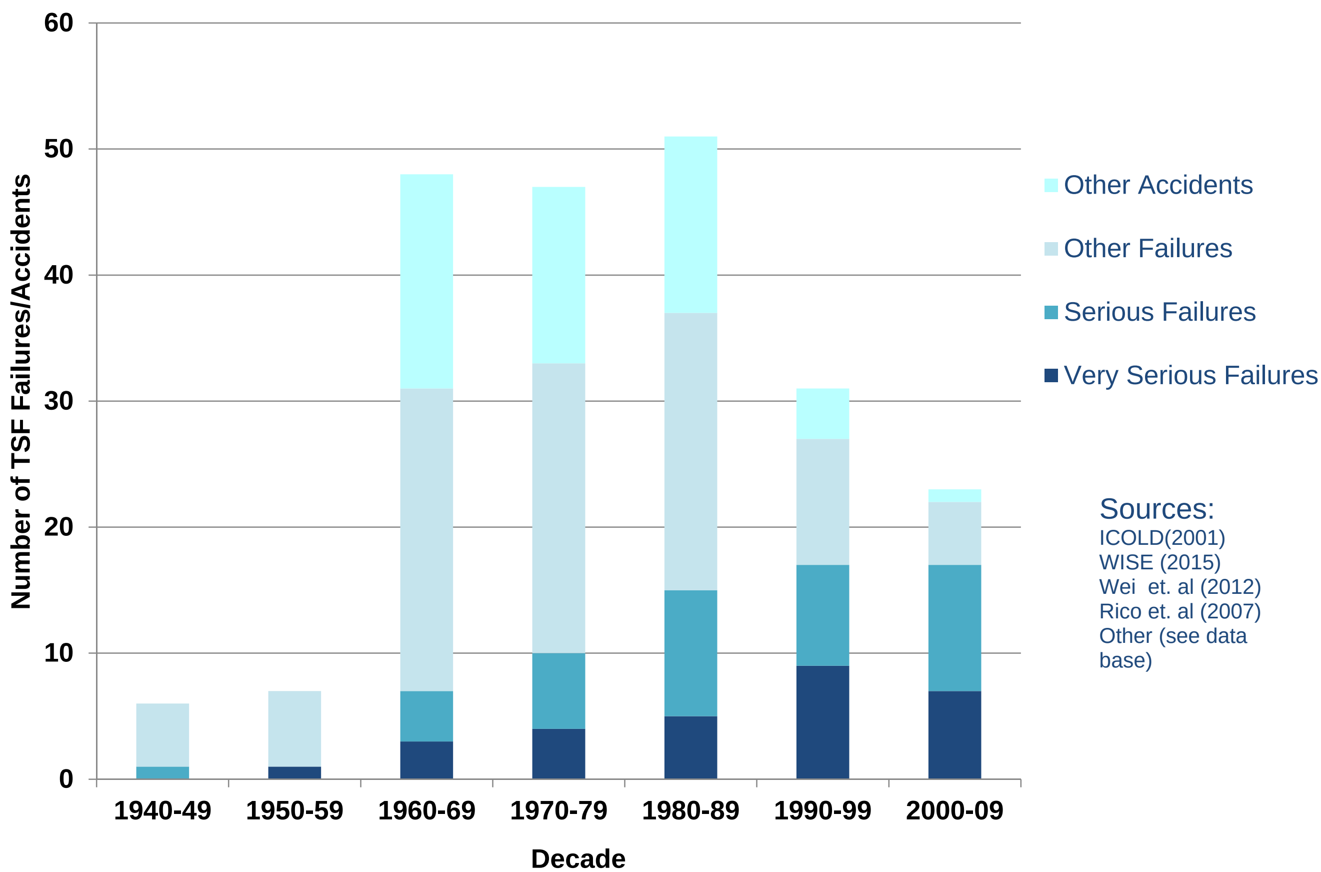
For this study we are interested primarily in the history and trend of Serious and Very Serious Failures rather than all incidents in the International Commission on Large Dams (ICOLD) or the World Information Service on Energy (WISE) compilations. These are the failures that cause consequential compromise of environmental security beyond the mine site. Serious and Very Serious failures accounted for 31% (67) of the 214 TSF failures and accidents 1940-2010, but comprise 63% (33/52) of the 52 total incidents, 1990-2010, with sufficient data for meaningful analysis.

We defined Serious failures as having a release of greater than 100,000 cubic meters and/or loss of life. 38 recorded incidents out of the 214 failures and accidents in the period 1940 to 2010 (18%) that had sufficient data for analysis met that criteria. 17 of those (45%) occurred in the last two decades.

We defined Very Serious failures as having a release of at least 1 million cubic meters, and/or a release that travelled 20 Km or more, and/or multiple deaths (generally ≥ 20). Very Serious failures comprised 14% of total historic events (29/214), but 31% (16/52) of all incidents and events in the past two decades (1990-2010). The complete list and criteria is presented in Appendix 1, TSF Failure Data Table.

This very clear trend to larger and more consequential losses is apparent in Figure 2.1 below. The clear aqua and paler blue is the distribution of incidents other than failures, most of which are very small with little or no release or consequential damage. Prior to 1980 Other Failures and Accidents (pale and aqua blue) were most prevalent. Post-1990 Serious and Very Serious failures (deep and dark blue) dominate.

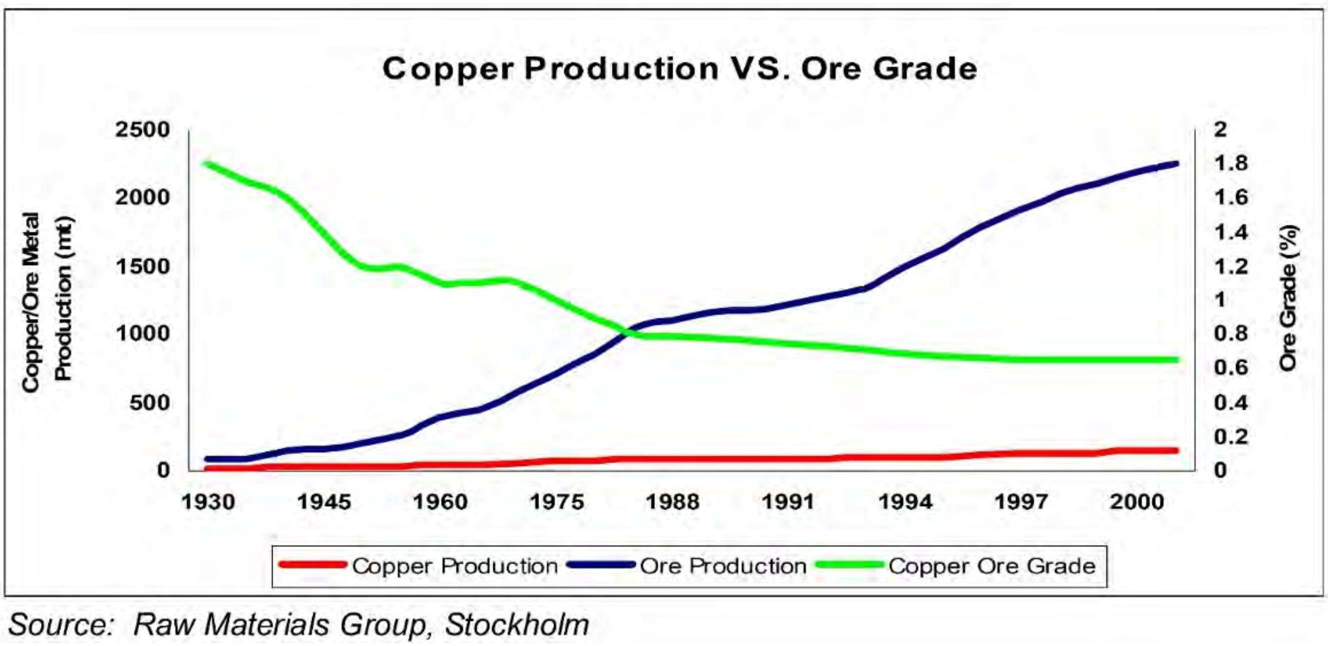
Figure 2.1 Increasing Severity of TSF Failures Globally 1940-2010



3.0 RELATIONSHIP BETWEEN LARGE FAILURES & THE MINING METRIC

Our aim was to explore the relationship between economic factors not explicitly accounted for in the permitting and regulatory oversight of mines and the observed trend toward failure incidents of greater consequence. Our data base included a count by decade of failures (Serious failures, Very Serious failures, Other failures, and Other Accidents) and a data set of variables describing the main economic trends driving mine production: price, costs to produce and grade. The following chart for copper prepared by the Raw Materials Group for the World Bank (World Bank 2006) describes the generic fundamental elements of the Mining Metric affecting all primary metals and most precious metals.

Figure 3.1. Copper Production & Ore Grade

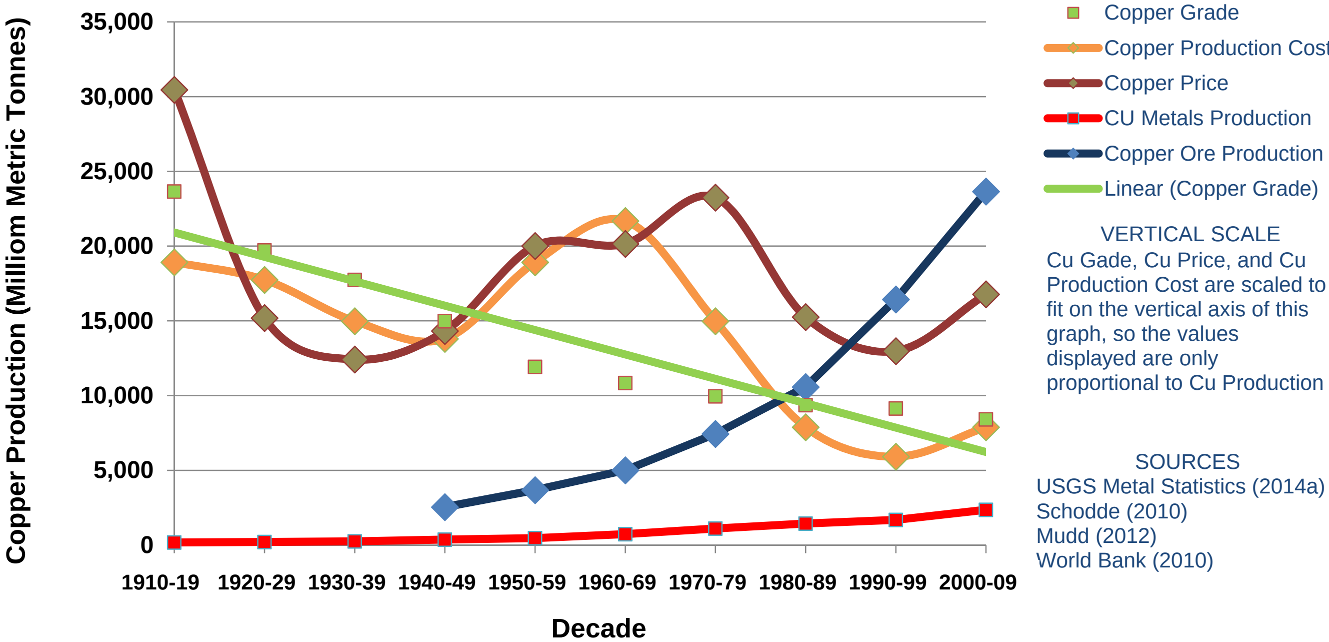


The chart is highlighting the very dramatic change in the relationship between metals output (the red line) which increased only 17% over the decade 1990-2000 and ore production[6] which increased 63% as grades continued to decline. The two key elements missing from this chart that explain how it was possible to "grow the resource" against a long trend of falling prices and falling grades the economic viability of these trends are the market price of the red line (the final refined product) and the costs to produce are highlighted by Richard Schodde, who noted that the declining costs to produce more than offset a century of falling prices. (Schodde 2010)

This fuller context is shown in Figure 3.2 below. That production costs have offset price is apparent through 1990.

[6] In our analysis we have used copper ore production data taken from the World Bank/Raw Materials Group graph because it is the only available published data for copper ore production. We have also done a comparison by using average copper ore grade and metal production to back-calculate to ore produced. For the back-calculation we used metal production data from Kelly & Matos (USGS 2014a), Schmitz/ABARE (Mudd 2012), the International Copper Study Group (ICSG 2014), and copper grade data from Mudd (2012). These data compared very favorably with the World Bank/Raw Materials Group data. We made several attempts to contact the Raw Materials Group through their corporate parent, SNL Metals & Mining, in an attempt to both verify the data (World Bank 2006) and the method(s) they used to develop it, but did not receive a response to these inquiries.

Figure 3.2 Mining Metric 1910-2010
Declining Prices Offset By Lower Production Costs



In correlation analysis, Table 3.1, price had a lower correlation than production cost with all failure classes. The most significant correlations with the four failure variables were with Cu Production Cost, Cu Grade and annual Cu Ore Production volume and Cu Metal Production. The correlations were only notable with the two highest failure severity categories. Cu Metal Production had higher correlations with both Very Serious failures (0.881) and Serious failures (0.826) as compared with Cu Ore Production. Cu Ore Production is more closely related, however, to TSF waste volume and also seems to distinguish between the two highest severity classes. This small difference also occurs with Cu Grade (greater negative for Serious) and Cu Production Cost (greater negative for Very Serious).

Table 3.1 Correlation Between Failure Severity and Mining Metric Indicators

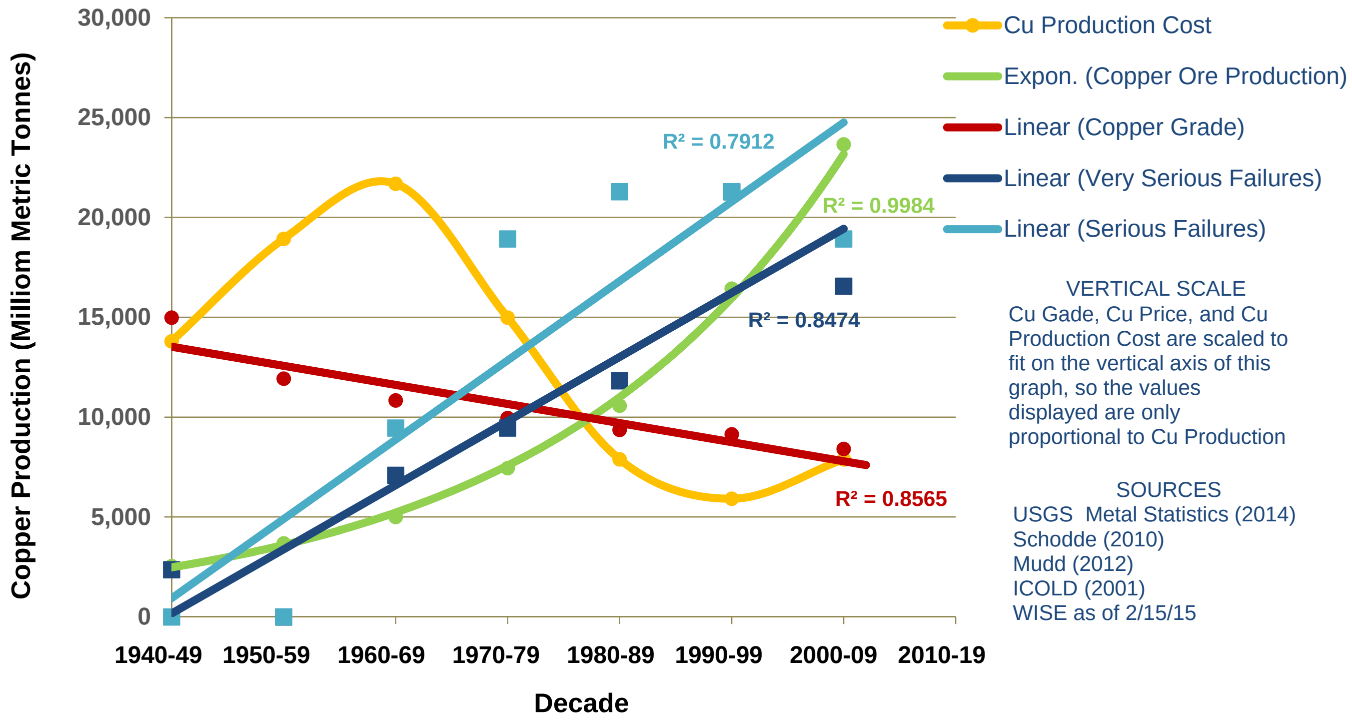
	Cu Ore Production	Cu Metal Production	Cu Grade	Cu Prod Cost	Cu Price
Very Serious Failures	0.860	0.881	-0.794	-0.788	-0.427
Serious Failures	0.720	0.826	-0.884	-0.682	-0.126
Other Failures	-0.265	-0.099	0.298	0.300	0.489
Other Accidents	-0.216	-0.050	-0.312	0.281	0.485

Abbreviations:
Cu Prod Cost = Cost to produce copper concentrate from copper ore, including waste disposal
Cu Grade = grade of copper in the ore
Cu Prod = copper ore production
Other Failures = tailings dam failures and incidents other than Serious or Very Serious Failures
Serious Failures = Serious tailings dam failures
Very Serious Failures = Very Serious tailings dam failures

Sources: USGS Metal Statistics (2014a), Schodde (2010), ICOLD (2001), WISE (2015) & additional

Therefore, we chose Cu Ore Production, Cu Grade and Cu Production Cost to produce for further analysis. We did not include, or have a basis for deeper consideration, of copper price. These relationships are graphically presented in Figure 3.3 below.

Figure 3.3 Relationship Between Mining Metric and TSF Very Serious and Serious Failures 1940-2010



The key mining metric variable, Copper Production Cost to produce, dropped from $85/tonne in 1900 to only $15/tonne in 2000. Over this same period price dropped from $7,723/tonne to $3,292 per tonne. The largest cluster of Serious and Very Serious failures of TSFs, 88% (59/67), occurred in the long downward price trend from 1970 to 2000. 86% (25/29) of Very Serious failures and 89% (34/38) of Serious failures occurred during this period. 2000 marked the beginning of an upward trend in price but also a 33% increase in costs to produce, from $15/tonne in 2000 to $20/tonne by 2010 but with Serious and Very Serious failures still representing 71% (15/21) of all failures for the decade 2000-2010.

The dramatic shift emphasized in the World Bank/Raw Metals charts (Figure 3.1) co- occurs with an upward swing in costs to produce while grade continues to fall (Figure 3.3). This suggests a higher level of financial risk beginning in 1990, which co-occurs with the emergence of Very Serious TSF failures.

Our data suggests that the many smaller mines and miners that became part of global production of all primary and precious metals post-1950 were not as able to take full advantage of as many of the technologies and economies of scale as larger miners, and therefore remained more sensitive to price changes than larger miners, with frequent shutdowns in a small portfolio of investments as price changes made continued production unviable. Smaller miners run on thinner balance sheets with more price vulnerability in comparison to the larger miners.

Another major factor affecting stewardship for TSFs and other mining environmental liabilities, which was not mapped sufficiently for inclusion in our database, is access to capital markets. Smaller mines have always had access only to more risk tolerant markets, such as the Toronto Stock Exchange, and sometimes, as in the case of Mt. Polley, with one or two specific backers. The top miners are financed through markets with tight, well defined credit standards and an increasing underwriting emphasis on full disclosure and accounting of environmental liabilities. Smaller miners have almost no meaningful access to insurance for their environmental liabilities, whereas larger miners have more integral relationships with insurance and reinsurance markets (even though the types of risks that are insurable are no different between large and small insurers). These large market relationships create more external accountability to environmental risk management and to financial risk management for larger miners than exists for small miners, and a more rigorous ongoing process of review and reckoning. Regulatory structures don't include enough structure on assessment of financial capacity to balance that difference creating an "apparent norm" of higher financial risk in smaller mines that translates into the higher losses we see in the historical data.

Two significant changes in financial risk also weigh more heavily for smaller mines than for larger mines: a radical contraction of all capital markets for mining (Jones 2014); and, a 30% increase in costs to produce. The increase in costs to produce is across the board and attributable, according to informed market analysts, to both an increase in energy costs and also in foreign exchange rates. Chile, a major producer of copper globally, has had to commit to a major capital program to improve its mining infrastructure to maintain grade and hold its place in world concentrate markets.

While each principal base metal (iron, aluminum, copper, zinc, etc.) has its own version of the Mining Metric, the basic "shape" and slope of trend lines for production and price for all base metals are the same. The basic bottom line, vis-a-vis manifest environmental loss across all metals, is the same. All operate on close margins. Those with larger budgets, better quality assets, lower production costs and uniform corporate policies on optimization and efficiency at each site, and who can also achieve economies of scale, will generally fare better than smaller miners with tighter budgets and less access to global capital markets. The global capital markets are able to provide external checks and balances on financial/risk management relationships that hold miners to account on environmental liability management, even when regulatory structures don't – but only if the miner in question is working in the global capital market.

Copper is widely recognized as a bellwether base metal for the mining industry. Most works on mining economics use copper as the "index metal". Beyond that, the greater quality and detail of regularly produced copper commodity information over the entire last century led us to explore its use as the index metal for TSF failures, i.e. expressing TSF failures per million tons of copper production. The USGS publishes metal statistics on two of Mining Metric elements, price and mine production, but no historical data on costs to produce or grade. So copper is the only metal for which it was possible to establish a full century long "actuarial" data base on the relationship between the economics of mining and environmental loss attributable to TSF failures. Going forward it will be possible to build the data base for other metals from current and data and short term projections. In the next section we present the statistical correlation between mining economics and TSF failures.

4.0 The Statistical Correlation between Mining Economics & Environmental Loss from TSF Failures

We chose Canonical Correlation Analysis (CCA) as a way of further exploring the relationship between the failure severity categories we created for this research and the main elements of the mining metric that affect all miners and all mine sites. We were interested in knowing whether there is a significant relationship and if so, whether it warrants greater attention in permitting standards and oversight of mine permits. We know from past study of TSF failures that there are many physical attributes of a TSF that influence severity as well as other often noted but so far unstudied factors such as the structure of the regulatory framework and the technical capacity available to oversight.

Canonical Correlation is a multivariate technique that aims at identifying the degree of influence of one data set with another (rather than causality). We had no pre conceived notion of what the degree of influence might be, nor did we have the data set we would like to have had. Nevertheless, the results of this exploration strongly suggest that the influence of the mining metric on frequency and severity of TSF failure is unexpectedly strong.

The First Canonical variant F1 explained 95% of the variability between the two data sets (failures v mining metrics elements). The correlations between F1 and both high severity variables are strong: Very Serious (-0.922); and, Serious (-0.995). The Wilks Lambda on F1 was 0.046 indicating a high degree of certainty that the two data sets (Failures and Mining Metric are not independent of one another). The Eigenvalue for F1, 0.903, suggests a very strong linear relationship between the two data sets (See Appendix 2, Technical Documentation on Canonical Correlation Analysis, for the data set and complete technical documentation on the Canonical Correlation).

Table 4.1 Canonical Correlation Values

	F1
Canonical Correlation	0.950
Eigenvalue	0.903
Wilks' Lambda	0.046
Correlation between:	
Very Serious failures & F1	-0.922
Serious failures & F1	-0.995

Because no other research team that we could find had explored the dimensionality of this relationship, we began with a larger set of mining metric variables beyond the 4 basic variables (Cu Production, Cu Production Cost, Cu Price and Cu Grade), and also attempted to create variables indicating the characteristics of TSF's so that the degree of influence of the mining metric variables could be compared with dam characteristics. We integrated all ICOLD/WISE recorded incidents from 1910 to 2010 into a single reconciled data set, and in the course of our research on consequence of those incidents discovered several compilations that added to WISE/ICOLD, and which also filled in gaps on our main indicators of consequence (total TSF release and release run out). We used both correlation matrix analysis and canonical correlations to find the strongest set of mining metric variables, which turned out to be tons of Cu Ore Production, Cu Production Cost, and Cu Grade. As there was only one recorded Serious failure prior to 1940 and very little information on all incidents, our final data set and analysis focused on the period 1940-2010.

Initially, none of our created synthetic variables for the Mining Metric were as strong the four main variables (copper price, production cost, grade, and copper ore production). One variable, Risk Factor, which combined cost and production volume into a single indicator actually had higher correlations with each of the two most Serious failure categories and also in linear regressions on each of the two highest severity categories. It did not perform as well in lieu of production and cost, though, in a canonical correlation. Further work is needed to evaluate Risk Factor so we are not presenting it here. Within the 4 basic variables price and cost canceled each other out, and cost was the stronger correlation, so the final data set for the Canonical Correlation was only cost, production and grade.

We were not able to develop a meaningful data set on dam characteristics for comparisons of degree of influence as between the variables of the Mining Metric and various dam characteristics (dam height, volume, etc.).

Even though these results are not conclusive, because the number of observations is very small for a CCA, they are persuasive evidence of a greater than expected and very significant influence of Mining Metric mega trends on the frequency and severity of TSF failures. Further, it is important to note that these are not “individual measurements” in the usual sense, but rather aggregations by decade of over 200 observations, and so should be afforded more consideration and weight than would normally attend such a small set of observations. The data set and the full CCA output are at Appendix 2, Technical Documentation on Canonical Correlation Analysis, along with additional technical annotation.

Although further research would be useful to shed more light on how these mega trend variables interact to affect failure, these results in our opinion support a conclusion that financial feasibility of the mine and financial capacity of the miner require greater specific consideration on permit issuance and permit oversight.

Strength of Influence of Copper Ore Production

Among the variables in the Mining Metric data set we were especially interested in the relative degree of influence/connection between copper ore volumes and the TSF failure categories especially whether it could be a reliable denominator for TSF failure rates. The conventional one to one correlations, which are a standard output of CCA in XLSTAT©, showed that both Very Serious and Serious failures were strongly correlated with copper ore production, 0.860 and 0.720 respectively. We had both production and price data on all metals 1900-2010 from the USGS metal statistics (USGS 2014a), but the correlations with aggregate all metals production and the failure variables were not nearly as strong. So the CCA output also lent support to copper ore production as the most reliable and meaningful denominator for TSF failure rates.

Although we did reasonably form an expectation that the mega trends would have a measureable and significant effect on the failure categories established (i.e. that the mega trends contribute to severity), we also know from dam committee reports and other research that many other dam specific elements have a known effect on severity of failure. The final output of a canonical correlation is a set of synthetic variables which maximize the accounting for mutual variability between the two sets of variables. Thus it is an approach which inherently recognizes that all of the information needed to explain the output of interest, the severity of failures over time, are not contained in the analysis, and further that the influence that may exist within in the expected determinant set (the mega trend variables) may result from complex interactions among the determinant data set.

While Canonical Correlation Analysis, and its focus on dimensionality rather than causality, may be the perfect tool for exploring the effect of mega trends of the Mining Metric on the trends in severity of TSF failures, many key variables that would shed more light were not available. We would hope in the future to have a more rich and complete data set, including standing TSFs that didn’t fail with the same geographic distribution as those that did.

At present there is no comprehensive compilation of recent or historic tailings dam failures. This is partly understandable given the multi-national nature of the mining industry, but given the severity of the problem, coupled with the fact that it is probably not realistic to think that the problem can be solved without a full analysis of the nature of the problem, it is disappointing that someone has not stepped forward to perform this service.

5.0 FREQUENCIES & PROJECTIONS FROM COPPER PRODUCTION VOLUMES

The results of the correlation analyses give strong support that copper production volumes are a meaningful denominator for TSF failures. Even if there were a centrally professionally maintained inventory of TSFs it would, in our opinion, still be preferable to express TSF failures on the basis of mine production.

Copper metal production is the only reliably managed data element we have available globally that correlates directly with TSF risk potential. The analysis shows us, however, that copper ore production distinguishes more clearly between the two high severity failure categories and is a better descriptor of risk. While it is not routinely and authoritatively compiled and reported as metal production is, the World Bank/Raw Materials Group data (Figure 3.1) did give us an authoritative and reliable historical compilation. As ore production volume is more directly related to TSF waste, in our opinion Cu Ore Production is the better predictor to use. We don't have a global census inventory of standing TSFs. To be meaningful any denominator must be available for all TSFs globally as it is only through data on the global whole that meaningful expectations and comparisons can be made at the level of a nation, province or state.

Secondly, we know there is a great deal of variation in the standing operating TSFs at any point in time. Size and therefore possible maximum consequence of failure varies from small mines with a total capacity of less than 10^5 cubic meters to those over 10^7 cubic meters. Therefore, failure frequency per TSF isn't meaningful without enough attending globally available data to adjust for size and other known risk factors. Post failure it is possible to reexamine the losses more closely, taking account of the specific characteristics of the particular TSF (and eventually to recompile findings if enough new information is developed or if there is more systematic capture of these elements in WISE or other data sources).

Thirdly, we know that the risk profile of TSFs is constantly changing based on production volumes, and how the waste volumes generated from that production are managed. We know that 90% of all TSF failures in Europe (Rico et. al. 2008), to 95% in China (Wei et. al. 2012), occur during operations, as opposed to being in standby or in closure. Cu Ore Production provides an equalized basis for looking across an inventory of TSFs with highly varying size, and it is more directly tied to the phase of active life for the TSFs in which most failures occur (Rico 2008).

Table 5.1, below, shows the failure incidents data for Very Serious failures, Serious failures and Other failures by decade, expressed per million tons of copper ore production. For example, a 0.0020 rate for Other failures in 1940-1949 on 2,545 million tons of ore production describes 1 event. A 0.0006 rate on 16,437 million tons (16.44 billion) of ore production in 1980 describes 10 Other failure events.

Table 5.1 Failures per Million Tonnes Copper Mine Production 1940-2011

Decade	Cu Ore Prod (MMt)	Very Serious failures (#)	Very Serious failures rate	Serious failures (#)	Serious failures rate	Other Failures (#)	Other Failures rate	Other Accidents (#)	Other Accidents rate
1940-49	2,545	1	0.0004	0	0.0000	5	0.0020	0	0.0000
1950-59	3,680	0	0.0000	0	0.0000	7	0.0019	0	0.0000
1960-69	5,004	3	0.0006	4	0.0008	25	0.0050	17	0.0034
1970-79	7,445	4	0.0005	8	0.0011	23	0.0031	15	0.0020
1980-89	10,575	5	0.0005	9	0.0009	22	0.0021	14	0.0013
1990-99	16,437	9	0.0005	9	0.0005	10	0.0006	3	0.0002
2000-09	23,658	7	0.0003	8	0.0003	5	0.0002	1	0.0000
Total/Ave	69,344	29	0.0004	38	0.0005	97	0.0021	50	0.0010

Abbreviations:

Cu Prod = copper ore production in the decade noted in millions of metric tonnes

Very Serious failure = multiple loss of life (~20) and/or release of ≥ 1,000,000 m^3 semi-solids discharge, and/or release travel of 20 km or more.

Serious failure = loss of life and/or release of ≥ 100,000 m^3 semi-solids discharge

Other failures = ICOLD Category 1 failures other than those classified as Very Serious or Serious

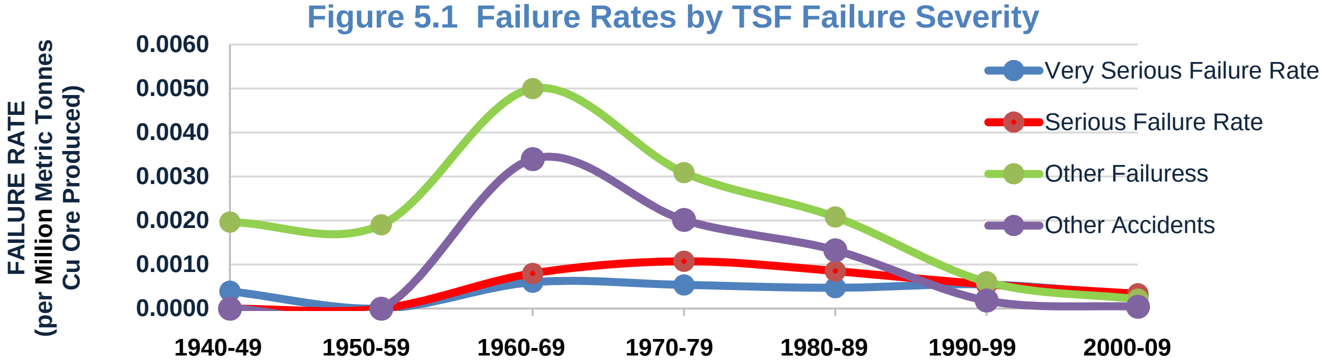
Other Accidents = ICOLD Category 2 accidents other than those classified as Very Serious or Serious

Failure Rate = number of failures per million metric tonnes (MMt) Cu Ore Produced

The overall rate of Very Serious failures and Serious failures 1940-2010 were comparable, 0 00004 and 0.0005 respectively. As expected, the higher the severity the lower the frequency. The frequency rates for all the lower severity loss categories were much lower; 0.021 Other Failures, 0.0010 for Other Accidents.

As shown in Figure 5.1 below the most dramatic change occurred with the shift from predominantly Other Failures (less Serious failure events) to predominantly more Serious failures post 1970. Across the board for each failure category, the rate of failure per ton of copper production has decreased. However, as noted in the introductory section, the severity of failures has steadily increased. More of the failures that occur are Serious or Very Serious). Our data is incomplete (we don't have actual loss data for every Serious and Very Serious failure), however it is certain that that the absolute consequence of all TSF failures has increased and is increasing substantially. This is obvious in that 55% (16/29) of all catastrophic (Very Serious failures) over the past 100 years have occurred since 1990, and that 74% (17/23) of all failure events post-2000 are Serious or Very Serious.

Figure 5.1 Failure Rates by TSF Failure Severity

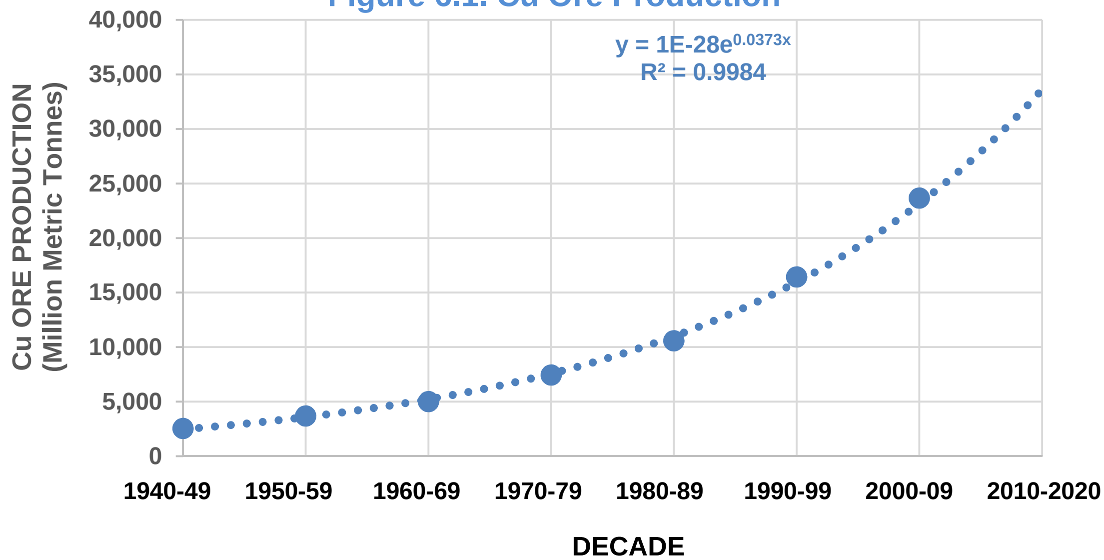


6.0 Projections from Copper Mine Production v. Failure Trends

The heart of risk analysis is to reliably measure and forecast expected losses that are beyond control (and to hopefully finance these losses via third party transfers, i.e. insurance or risk pool). We know that will not apply to TSF failure losses, as almost without exception all losses were subject to control and prevention. The basic techniques for forecasting future losses, based on past loss experience, are nevertheless applicable to anticipating the future consequences of continuing the Mining Metric without some new forms of regulatory control and oversight which takes more adequate account of the financial viability of the deposit and the miner.

The Copper ore production estimate for this decade (2010-2019) is advanced from the equation associated with the trend line which had an extremely high R square, 0.9984. The result is 36,338 million metric tonnes, a projected increase of 54%.

Figure 6.1. Cu Ore Production



In insurance rate making the normal procedure for estimating future losses is to combine the last four years of loss data. For this data, though, each cell represents 10 years of experience data not 1, and we can see from analysis of the variables over 100 years that the events that shape loss and failure are unique to each decade, i.e. that each decade has its own pattern of determinant/loss-affecting characteristics.

Table 6.1 below compares three estimates of next decade failures based on three approaches to uses of copper production based frequencies: (1) average of last three decades; (2) last decade only; and, (3) "50-50" weighting between most recent decade and last three decades. The trended values based on failure data alone are presented in Table 6.1 in the last row of the table.

The chart values in Table 6.1 are computed from the trend line equations as they appear in Figure 6.2 (The trend lines in Figure 6.2 are linear data projections, rounded to the nearest whole number).

Very Serious failures 2020 = 0.1393*2020-271.64 = 9.746

Serious failures = 0.1643*2020-3189.6 = 12.026

Table 6.1 Predictions 2010-2020 From Historic Failure Rates

Basis	Very Serious failures Rate	Very Serious failures Pred.	Serious failures Rate	Serious failures Pred.	Other Failures Rate	Other Failures Pred.	Other Accidents Rate	Other Accidents Pred.
Last 3 Decade Ave	0.0004	15.9	0.0006	21.0	0.0010	35.1	0.0005	18.8
Last Decade	0.0003	**10.8**	0.0003	**12.3**	0.0002	7.7	0.0000	1.5
50-50 Weighting	0.0004	13.3	0.0005	16.7	0.0006	21.4	0.0003	10.1
Chart		**9.5**		**12.0**				

Rate = number of failures per million metric tonnes (MMt) ore mined

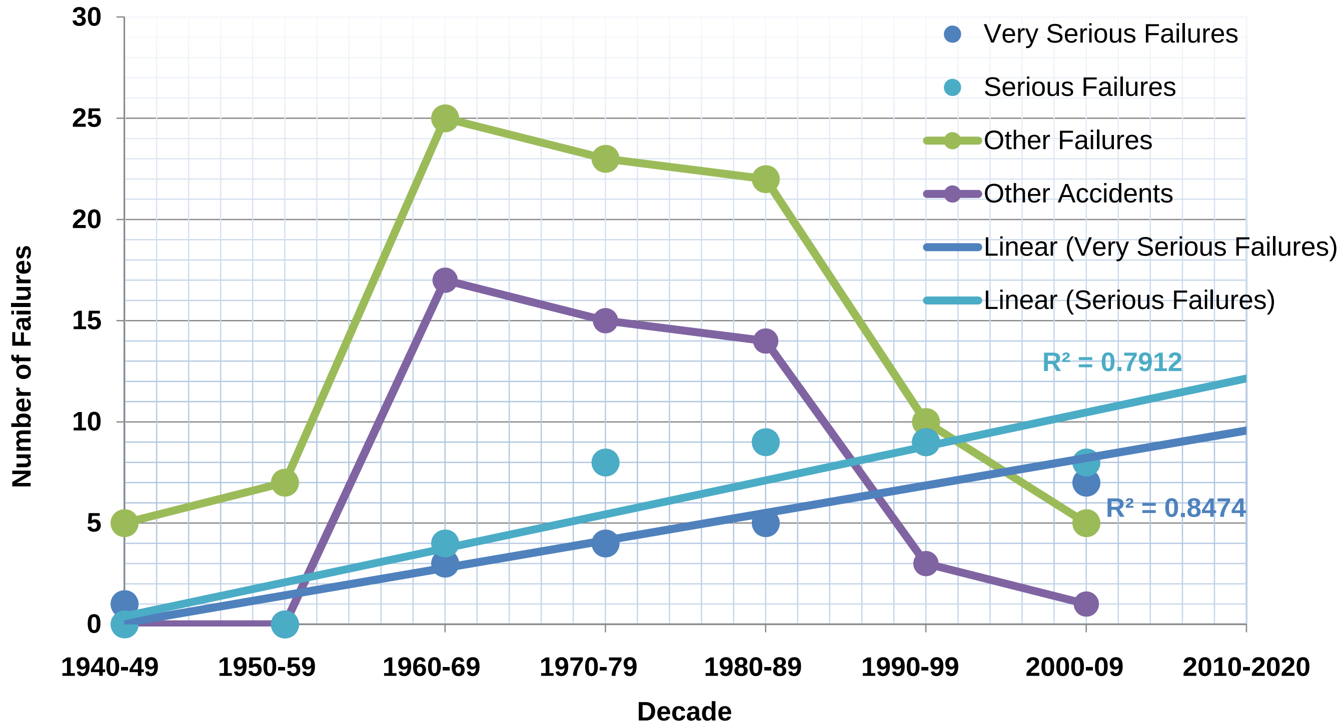
Pred = number of predicted failures in the period 2010 - 2019

The high R-squared values on the trend lines for both Serious failures and Very Serious failures indicate a "goodness of fit" that is apparent on visual inspection alone (i.e. the markers closely track the trend line). The calculated predictions by chart trend line equation most closely matches the prediction based on the most recent decade failure rates.

The canonical correlation demonstrates that the trends in the high severity failures are shaped by the entire metric (as represented in grade, cost and production). Inspection of the data set shows that the main elements of the metric as of 2009 were very different than those of either of the prior two decades. It is not likely costs will return to as low as $15 or that prices will fall to as low as they were in either of the two most recent decades. Therefore we have greater confidence in the most recent failure rate by class than we do in the either the average of the last three decades, or a 50-50 weighting between the average of the last three decades and current decade. Still there are already clear indications that this decade involves uncertainty about the direction of cost to produce, price, and perhaps even production volumes. The previous two decades both had constant costs of production against failing prices, a very different pattern with an expected higher rate of failure. Mid-decade 2010-2019 the overall environment seems to be trending toward higher financial risk, and therefore higher potential environmental liability than the 2000-2009 decade.

We are though projecting 12 Serious failures and 11 Very Serious failures for the present decade (2010–2019) relying on the failure rates of the most current decade (see Table 6.1).

Figure 6.1 Failure Predictions By Trend Line



Our dataset included 5 failures 1910-2010 that met our criteria for Very Serious that were not listed in WISE or ICOLD data bases, from a compilation of Chinese major failures and a compilation of Philippine significant tailings incidents. The frequency rate 2000-2009 was essentially the same with or without these five failures. We cannot say that whatever undercount actually exists in WISE/ICOLD data would have no bearing, however, in our view this is a conservative projection quite apart from the possible undercount issue. It makes no allowances for the possibly higher risks of price jitters on many metals (e.g. molybdenum, iron, zinc, gold), of rising production costs mostly from energy and foreign exchange rates, and the uncertainty about the roles China, Chile, and Peru (as producers, and China and India (as consumers) will play, and how that could elevate financial risks for smaller mines and smaller miners.

7.0 Projected Cost of Remediation and Non Remediable Uncontrolled releases from TSFs

We searched the historic record for what local authorities had deemed the costs of public damages from the major releases in our database, and found sufficient authoritative documentation on a total of 6 of the 14 post-1990 Very Serious uncontrolled TSF originating release incidents. Our process was to translate from foreign currency to US in the year of the incident and then to convert those $US to 2014-$US. The average cost of the 7 incidents for which we found authoritative data was $543 million (Figure 7.1). That translates to a projected public liability for remediation of 11 Very Serious releases from TSFs at cost of approximately $5 billion globally before the end of this decade (2020). We did not attempt any estimates for the expected 12 Serious failures by 2020 but a guess of an additional $1 billion is probably not unreasonable.

Usually losses are forecast from a record of homogeneous data maintained by one source over time by the entity which has actually incurred or paid out those losses (i.e. an insurer or a rating bureau like the Insurance Services Office), or a company's or agency's risk manager. That is not true of our loss history data for TSF failures. Although WISE has followed with some detail on a few cases involving litigation for recovery of outlays (e.g. for Los Frailes), descriptions of consequence are brief and narrative. There are few links to more in-depth authoritative analysis on consequence. Losses are not systematically or uniformly captured or developed as part of either the WISE or ICOLD databases. The costs data we present here is all we could find for Very Serious post-1990 failures which pertained to environmental losses, and which were cited or developed by authoritative or credible sources.

We aimed for as much homogeneity as possible in choosing amounts documented for inclusion in our loss history (i.e. to include only natural resources/environmental losses whether or not cleanup was ordered or undertaken. In one case, Omai, we used a token amount to acknowledge what farmers, fisherman, and NGOs attempted to recover, and to acknowledge what is widely agreed was environmental damage notwithstanding the governments judgments to the contrary. The token amount allocated to Omai actually lowers the overall average cost estimate but, given all the litigation and controversy that has attended, simply admitting to the extent of environmental damage we felt Omai could not simply be left off the list, even though we could not find documentation on what part of $2 billion joint damage claim was attributable to documented environmental damages to lands and waters.

While sketchily sourced and documented, the few failures which are systematically and authoritatively developed give us a high level of confidence that our average natural resource loss of $543 million for a catastrophic failure is not overstated. For example, the estimated costs to clean up the Los Frailes spill was borne primarily by the Andalusian Government as a non-remediable loss. We think that situations like this, where the actual costs are so high or cleanup costs so astronomical that losses from Very Serious TSF failures will more and more be permanent non-recoverable losses. Mt Polley is a possible example of a tailings spill into a creek and lake that will not be retrieved. Such losses will, hopefully, still have a complete accounting of value whether or not remediation is ordered, undertaken, or possible.

The data on the 7 failures forming the basis of our average loss amount of $543 million and its sources are presented in Table 7.1, below. See Appendix 3 for more detail on this chart.

Apply this to our projections of the number of Very Serious failures, 11 results in a projected unfunded unfundable public liability loss of $6.0 billion from Very Serious TSF failures for the decade 2010-2019.

Our sense of the data and case histories is that this decades' TSF failures will continue to arise mostly from standing operating TSFs, pushing older TSFs up to and past their original designs, or stretching the limits of TSFs that were not built or managed to best practices in the first place. We expect most to arise from smaller mines and miners. We see in the record an indication that in many instances releases and events suggesting fundamental problems with the structure of the TSF preceded a final catastrophe by two to four years. In the cases of Golden Cross (New Zealand), Bingham Canyon (Utah), and Mike Horse (Montana) long term issues with dam stability led to closures in time to avert catastrophe at costs that were significantly lower than the remediation costs or assessed damages would have been for a structural failure.

Table 7.1 Documented TSF Very Serious Natural Resource Losses 1990 – 2010

TSF Failure	Year	Original Currency (Millions)	Failure Year M US$	2014 M US$	Ore	Release (M m^3)	Run Out (km)	Deaths
Kingston Fossil Plant, Harriman, Tennessee, USA	2008	US 1,200	$1,200	$1,300		5.4	4.1	
Taoshi, Linfen City, Xiangfen, Shanxi Province, China	2008	US 1,300	$1,300	$1,429	Fe	0.19	2.5	277
Baia Mare, Romania	2000	US 179	$179	$246	Au	0.1	5.2	
Los Frailes, Spain	1998	EU 275	$301	$437	Zn/Cu /Pb	4.6	5	
Marinduque Island, Philippines	1996	P 180 + US 114	$123	$185	Cu	1.6	27	
Omai, Guyana	1995	US 100	$100	$156	Au	4.2	80	
Merriespruit, South Africa	1994	R 100	$29	$46	Au	0.6	2	17
		Average US$2014: $543		====== $3,799				

Reviewing their own role in creating and perpetuating the environment in which we have allowed TSFs at risk of consequential failure to proliferate, the International Bank for Reconstruction & Development and the International Development Association put it well:

> *"Governance should be strengthened until it is able to withstand the risks of developing major extractions. Once that has happened, the International Bank for Reconstruction and Development (IBRD) and the International Development Association (IDA) can add support for the promotion of a well-governed extractive sector. Similarly, when the International Finance Corporation and the Multilateral Investment Guarantee Agency (MIGA) consider investing in an oil, gas, or mining project, they need to specifically assess the governance adequacy of the country as well as the anticipated impacts of the project and then only support projects when a country's government is prepared and able to withstand the inherent social, environmental, and governance challenges." (IFC 2003)*

Our study has provided a very conservative estimate of future unfunded public liabilities for standing, already operating, and permitted TSFs globally. We know globally that every one of those failures can be prevented for a cost much less than $6.0 billion for just the 11 Very Serious failures we are predicting by 2020.

We know globally, and in Canada and the US, the regulatory structure is not presently in place to identify and correct these at-risk TSFs before they fail, and we know many of them are operated by companies whose balance sheets are too thin to fund repairs and closure where necessary.

We hope our work will begin a collaborative and highly focused multi-disciplinary dialogue to prevent the materialization of these $6.0 billion in public losses by 2020.

8.0 SUMMARY & CONCLUSIONS

The advances in mining technology over the past 100 years which have made it economically feasible to mine lower grades of ore against a century of declining prices have not been counterbalanced with advances in economically efficient means of managing the exponentially expanding volume of associated environmental liabilities in waste rock, tailings and waste waters. In fact those new technologies which do offer better management of mine wastes usually add significant cost and are often detrimental to bottom line financial feasibility. This is evidenced in a post-1990 trend toward un-fundable environmental losses of greater consequence. This interdisciplinary review of TSF failures 1910-2010 establishes a clear and irrefutable relationship between the mega trends that squeeze cash flows for all miners at all locations, and this indisputably clear trend toward failures of ever greater environmental consequence.

The implication of our findings is that a continuation of the present Mining Metric is not environmentally or economically sustainable, and that regulatory systems must begin to understand and address financial capacity of the miner, and the financial feasibility of mining itself, both in permitting criteria and in oversight of mine water management over the life of the mine.

Our findings point toward undocumented and unstudied risks of failure in the standing operating already permitted mines of smaller miners globally where cash flow pressures have led to an avoidance of best practices in waste management, and where political pressures have led to avoided close scrutiny of decades of neglect and shortfalls.

We have not identified an existing statutory or regulatory system anywhere that has the authority and capacity to identify and prevent the $6 billion in losses we estimate the public globally will be liable for by the end of this decade.

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APPENDIX 1

TSF Failure Data Table

TSF FAILURE DATA TABLE LEGEND

Very Serious	30	Very Serious = multiple loss of life (~20) and/or release of ≥ 1,000,000 m3 semi-solids discharge, and/or release travel of 20 km or more
Serious	38	Serious = loss of life and/or release of ≥ 100,000 m3 semi-solids discharge
Other Failures	98	Other Failures = ICOLD Category 1 failures other than those classified as Very Serious or Serious
Other Accidents	50	Other Accidents = ICOLD Category 2 accidents other than those classified as Very Serious or Serious
Non-Dam Failure	10	Non-Dam Failures = groundwater, waste rock, etc.
	=======	
Total	226	

SOURCES:

(1) ICOLD. International Committee on Large Dams, Bulletin 121 "Tailings Dams Risks of Dangerous Occurrences Lessons Learned From Practical Experiences"

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DAM TYPE Key		DAM FILL MATERIAL Key		INCIDENT TYPE Key			INCIDENT CAUSE Key	
US	Upstream	**T**	Tailings	**1A**	Failure	Active Impoundment	**SI**	Slope instability
DS	Downstream	**CST**	Cycloned sand ta	**1B**	Failure	Inactive Impoundment	**SE**	Seepage
CL	Centerline	**MW**	Mine waste	**2A**	Accident	Active Impoundment	**FN**	Foundation
WR	Water retention	**E**	Earthfill	**2B**	Accident	Inactive Impoundment	**OT**	Overtopping
NR	Not reported	**R**	Rockfill	**3**	Groundwater		**ST**	Structural
							EQ	Earthquake
							MS	Mine subsidence
							ER	Erosion
							U	Unknown, or
							NR	Not Reported

GENERAL NOTE

We found small variations source to source on total release, run out, deaths and other details, but we found no ambiguities or inconsistencies that precluded a clear classification as "Serious" or "Very Serious".

Overall we found much more detailed accounts of "consequence" in local compilations or regional or national studies. WISE & ICOLD occasionally including details on consequence, or linked to sources detailing consequence. Our bibliogtaphy includes a more extensive list of materials related to the consequence of TSF failures

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Karamken, Magadan Region, Russia					1A	29-Aug-09	1,200,000		1		WISE, MACE	11 houses lost, 1 death (Karamken Update - MACE 2012-02-10)
	Huayuan County, Xiangxi Autonomous Prefecture, Hunan Province, China					1A	14-May-09	50,000		3		WISE	3 killed, 4 injured
	Kingston fossil plant, Harriman, Tennessee, USA					1A	22-Dec-08	5,400,000	4.1			WISE	5.4 million cubic yards (1.09 billion gallons) of fly ash was released (http://www.sourcewatch.org/index.php?title=TVA_Kingston_Fossil_Plant_coal_ash_spill#TVA_Reaction)
	Taoshi, Linfen City, Xiangfen county, Shanxi province, China	US		50.7	290,000	1A	8-Sep-08	190,000	2.5	277		WISE	At least 254 dead and 35 injured.
	Glebe Mines, UK		E			1B-OT	22-Jan-07	20,000				HSE Report	Initial Report of the HSE investigation into the Glebe Mines Stony Middleton dam failure 2007, HSE Central Division - Nottingham, UK, 23Feb07
	Miliang, Zhen'an County, Shangluo, Shaanxi Province, China					1A	30-Apr-06		5	17		WISE	17 missing
	Pinchi Lake, BC, Canada	WR	E	12		2A-ER	30-Nov-04	6,000-8,000				WISE	Mercury contaminated tailings into Pinchi Lake
	Riverview, Florida, USA					1A	5-Sep-04	227,000				WISE	
	Partizansk, Primorski Krai, Russia					1A	22-May-04	166,000				WISE	
	Malvési, Aude, France					1A	20-Mar-04	30,000				WISE	Uranium slurries elevated nitrate in river
	Cerro Negro, near Santiago, Chile, (5 of 5)	US	T			1A-ER	3-Oct-03	80,000	20			WISE	
	El Cobre, Chile, 2, 3, 4, 5	US	T			1B-OT	22-Sep-02	8,000				Villavicencio (2014)	
	San Marcelino Zambales, Philippines, Bayarong dam (9/11/02)				47,000,000	1B	11-Sep-02					WISE, Piplinks	Sep. 11: low lying villages flooded with mine waste; 250 families evacuated;
	San Marcelino Zambales, Philippines, Camalca dam (8/27/02)					1B	27-Aug-02					WISE, Piplinks	Aug. 27: some tailings spilled into Mapanuepe Lake and eventually into the St. Tomas River.
	El Cobre, Chile	US	T			1B-OT	11-Aug-02	4,500				Villavicencio (2014)	
	Sebastião das Águas Claras, Nova Lima district, Minas Gerais, Brazil					1A	22-Jun-01		8	2		WISE	2 killed, 3 missing. Tailings 8 km downstream the Córrego Taquaras stream, mud affected an area of 30 hectares
	Nandan Tin mine, Dachang, Guangxi					1A	18-Oct-00			28		WISE, Wei	WISE:15 killed, 100 missing, 100 houses destroyed

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Inez, Martin County, Kentucky, USA					1A	11-Oct-00	950,000	120		Table 1	ICOLD, WISE	
	Aitik mine, near Gällivare, Sweden	DS	MW & E	15	15,000,000	1A-ER	8-Sep-00	1,800,000	5.2		Table 1	ICOLD, WISE	
	Baia Mare, Romania Esmerelda Exploration	DS then US	T	A few m	800,000	1A-ST	30-Jan-00	100,000	>100		221	ICOLD, WISE, Rico	Killed tonnes of fish and poisoned drinking water of more than 2 million people in Hungary
	Borsa, Romania					1A	2000	22,000t			Table 1	ICOLD, WISE	Company: Remin SA
	Surigao Del Norte Placer, Philippines (#3 of 3)					1A	26-Apr-99	700,000 t	12	4	Table 1	ICOLD, Piplinks	
	Toledo City (Philippines)					1B	1999	5,700,000				Piplinks	Drainage tunnel blowout
	Huelva, Spain					1A	31-Dec-98				Table 1	ICOLD, WISE	Fertiberia phosphate mine
	Los Frailes, near Seville, Spain	WR	R	27	15,000,000	1A-FN	25-Apr-98	6,800,000	41		209	ICOLD, WISE, Rico	
	Zamboanga Del Norte, Sibutad Gold Project					1A-OT	6-Nov-97					Piplinks	
	Pinto Valley, Arizona, USA					1B	22-Oct-97	230,000			Table 1	ICOLD, WISE	
	Amatista, Nazca, Peru					1A-EQ	12-Nov-96	300,000				WISE	due to M6.4 earthquake
	El Porco, Bolivia					1A	29-Aug-96	400,000	300		Table 1	ICOLD, WISE	300 km of Pilcomayo river contaminated
	Marcopper, Marinduque Island, Philippines(3/24) (#2 of 2)					1A-ST	24-Mar-96	1,600,000	26		208	ICOLD, WISE, Piplinks	Drainage tunnel plug failed. 26 km of the Makulaquit and Boac river systems filled with tailings rendering them unusable; US$ 80 million in damage
	Sgurigrad, Bulgaria	US	T	45	1,520,000	1A-SI	1996	220,000	6		220	ICOLD, Rico	
	Negros Occidental, Bulawan Mine Sipalay River					1A	8-Dec-95					Piplinks	
	Golden Cross, Waitekauri Valley, New Zealand		R	25-30	3,000,000	1A-FN	Dec-95	9,999			207	ICOLD	
	Surigao del Norte Placer, Philippines (#2 of 3)	WR	E	17		1B-SI	2-Sep-95	50,000		12	206	ICOLD, WISE	
	Omai Mine, Tailings dam No 1, 2, Guyana	WR	R	44	5,250,000	1A-ER	19-Aug-95	4,200,000	80		205	ICOLD, WISE, Rico	80 km of Essequibo River declared environmental disaster zone
	Middle Arm, Launceston, Tasmania	CL	E	4	25,000	1A-OT	25-Jun-95	5,000			204	ICOLD	
	Riltec, Mathinna, Tasmania	CL	E	7	120,000	2A-SE	Jun-95	40,000			203	ICOLD	
	Hopewell Mine, Hillsborough County, Florida, USA					1A	19-Nov-94	1,900,000				WISE	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Payne Creek Mine, Polk County, Florida, USA					1A	2-Oct-94	6,800,000				WISE	
	Merriespruit, near Virginia, South Africa, Harmony 2, 3	US paddock	T	31	7,040,000	1B-OT	22-Feb-94	600,000	4	17	202	ICOLD, WISE, Rico	
	Olympic Dam, Roxby Downs, South Australia					3	14-Feb-94	5,000,000				WISE	Designed groundwater leakage from unlined tailings impoundment into groundwater
	Minera Sera Grande: Crixas, Goias, Brazil	DS then US	CST	41	2.25Mt	2A-SI	Feb-94	None			214	ICOLD	
	Fort Meade, Florida, Cargill phosphate (#3 of 3)					1A	2-Jan-94	76,000				WISE	
	Longjiaoshan, Daye Iron Ore mine, Hubei					1A	1994			31		Wei	
	Marcopper, Marinduque Island, Mogpog Philippines(12/6) (#1 of 2)					1B	6-Dec-93			2		Piplinks	Siltation dam failure. Mogpog River and Mogpog town flooded.
	TD 7, Chingola, Zambia	US	T&E	5		1A-OT	Aug-93	100 t			200	ICOLD	
	Itogon-Suyoc, Baguio gold district, Luzon, Philippines					1A-OT	26-Jun-93				199	ICOLD, Piplinks	
	Marsa, Peru					1A-OT	Jan-93			6		WISE	
	Kojkovac, Montenegro	WR	E		3,500,000	2B-ER	Nov-92	none			198	ICOLD	
	Saaiplaas, South Africa, 2		CST			1A-IS	19-Mar-92				Table 1	ICOLD	3 separate events within 4 days
	Maritsa Istok 1, Bulgaria		Ash	15	52,000,000	1A-ER	1-Mar-92	500,000			218	ICOLD, WISE	
	Tubu, Benguet, No.2 Tailings Pond, Padcal, Luzon, Philippines				80,000,000	1A-FN	2-Jan-92	80,000,000			197	Piplinks	
	Iron Dyke, Sullivan Mine, Kimberley, BC, Canada	US		21		1A-SI	23-Aug-91	75,000			196	ICOLD	
	Soda Lake, California, USA	US	E	3		2A-EQ	17-Oct-89				111	ICOLD	
	Silver King, Idaho, USA	DS	E	9	37,000	2A-OT	5-Aug-89	Small			108	ICOLD	
	Big Four, Florida, USA	CL	E			2A-FN	1989				14	ICOLD	
	Cyprus Thompson Creek, Idaho, USA	CL	CST	146	27,000,000	2A-SE	1989				34	ICOLD	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Southern Clay, Tennessee, USA	WR	E	5		1A-SE	1989	300			112	ICOLD	
	Stancil , Maryland, USA	US	E	9	74,000	1A-SI	1989	38,000	0.1		116	ICOLD, Rico	
	Unidentified, Hernando, County, Florida, USA #2	US	E	12	3,300,000	1A-OT	Sep-88	4,600			163	ICOLD	
	Jinduicheng, Shaanxi Province., China	US		40		1A-OT	30-Apr-88	700,000		~20	195	ICOLD, WISE	
	Consolidated Coal No.1, Tennessee, USA,	DS	MW	85	1,000,000	2A-ST	19-Jan-88	250,000			121	ICOLD, WISE	
	Rain Starter Dam, Elko, Nevada, USA	WR	ER	27	1,500,000	3-	1988				98	ICOLD	
	Unidentified, Hernando, County, Florida, USA	DS	E	12		2A-FN	1988				164	ICOLD	
	Surigao Del Norte Placer, Philippines (#1 of 3)					1A	9-Jul-87					Piplinks	
	Montcoal No.7, Raleigh County, West Virginia, USA					1A	8-Apr-87	87,000	80			WISE	tailings flow 80 km downstream
	Bekovsky, Western Siberia	US	Argillite, aleurolite	53	52,000,000	1A	25-Mar-87	None			212	ICOLD	
	Xishimen, China	US	T	31		1A-SI	21-Mar-87	2,230			194	ICOLD	
	Montana Tunnels, MT, USA	DS	MW	33	250,000	3-	1987				87	ICOLD	
	Marianna Mine #58, PA,	US	E	37	300,000	2A-SI	19-Nov-86				77	ICOLD	
	Mankayan, Luzon, Philippines, No.3 Tailings Pond		E			1A-ST	17-Oct-86				193	ICOLD, Piplinks	Siltation of the Abra River which affected 9 municipalities
	Lepanto, Mankayan, Benguet, Philippines					1A	17-Oct-86					Piplinks	Siltation of the Abra River which affected 9 municipalities
	Pico de Sao Luis, Gerais, Brazil		T	20		1A-ER	2-Oct-86				192	ICOLD	
	Rossarden, Tasmania	WR	E	7.5	200,000	1B-OT	16-May-86				190	ICOLD	
	Story's Creek, Tasmania	Valley side		17	30,000	1B-OT	16-May-86	Minimal			191	ICOLD	
	Itabirito, Minas Gerais, Brazil	Gravity	Masonry	30		1A-ST	May-86	100,000	12	7	189	ICOLD, WISE, Rico	
	Mineral King, BC, Canada	CL	CST	6	Small	1B-OT	20-Mar-86				188	ICOLD	
	Huangmeishan, China					1A	1986			19		WISE	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Spring Creek Plant, Borger, Texas, USA			5	30,000	1A-OT	1986				114	ICOLD	
	Bonsal, North Carolina, USA	WR	E	6	38,000	1A-OT	17-Aug-86	11,000			17	ICOLD	
	Stava, North Italy, 2, 3	US	CST	29.5	300,000	1A-SI	19-Jul-85	200,000	8	269	117	ICOLD, WISE, Rico	
	La Belle, Pennsylvania, USA	DS	MW	79	1,230,000	2A-FN	17-Jul-85				68	ICOLD	
	Cerro Negro No. (4 of 5)	US	CST	40	2,000,000	1A-EQ	3-Mar-85	500,000	8		30	ICOLD WISE, Rico	
	Veta de Agua	US	T	24	700,000	1A-EQ	3-Mar-85	280,000	5		178	ICOLD, WISE, Rico	
	El Cobre No. 4	DS	CST	50		2A-EQ	3-Mar-85				44	ICOLD	
	Niujiaolong, Shizhuyuan Non-ferrous Metals Co., Hunan					1A	Jan-85	731,000	4.2	49		Wei	
	Marga, Chile					1B-OT	1985				76	ICOLD	
	Ollinghouse, Nevada, USA	WR	E	5	120,000	1A-SE	1985	25,000	1.5		91	ICOLD, Rico	
	Texasgulf 4B Pond, Beaufort, Co., North Carolina, USA	WR	T	8	12,300,000	2A-SI	Apr-84				122	ICOLD	
	Mirolubovka, Southern Ukraine	US	E&T	32	80,000,000	2A-SI	15-Jan-84	-			210	ICOLD	
	Battle Mt. Gold, Nevada,	DS	E	8	1,540,000	2A-SI	1984				11	ICOLD	
	Virginia Vermiculite, Louisa County, Virginia, USA	WR	E	9		1A-ST	1984				179	ICOLD	
	Clayton Mine, Idaho, USA	CL	T	24	215,000	2A-ST	2-Jun-83				32	ICOLD	
	Golden Sunlight, MT, USA	CL	CST			3-	5-Jan-83				51	ICOLD	
	Grey Eagle, California, USA	DS	E			3-	1983				53	ICOLD	
	Vallenar 1 and 2					1B-OT	1983				175	ICOLD	
	Sipalay, Philippines, No.3 Tailings Pond	WR	MW		37,000,000	1A-FN	8-Nov-82	28,000,000			187	ICOLD, WISE, Piplinks	Dam failure, due to slippage of foundations on clayey soils. Widespread inundation of agricultural land up to 1.5 m high
	Royster, Florida, USA	US	T	21		1A-FN	1982				102	ICOLD	
	Ages, Harlan County, Kentucky, USA					1A	18-Dec-81	96,000	163	1		WISE	
	Dixie Mine, Colorado, USA					1B-U	Apr-81				39	ICOLD	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Balka Chuficheva, Russia	US	CST	25	27,000,000	1A-SI	20-Jan-81	3,500,000	1.3		211	ICOLD, WISE	
	Texasgulf No. 1 Pond, Beaufort Co., North Carolina, USA	WR	E		24,700,000	2A-SI	1981				123	ICOLD	
	Veta de Aqua A					1A-EQ	1981				176	ICOLD	
	Veta de Agua B					1A-EQ	1981				177	ICOLD	
	Tyrone, New Mexico, Phelps-Dodge	US	CST	66	2,500,000	1A-SI	13-Oct-80	2,000,000	8		94	ICOLD, WISE, Rico	
	Sweeney Tailings Dam, Longmont, Colorado, USA			7		1A-SE	May-80				119	ICOLD	
	Kyanite Mining, Virginia, USA			11	430,000	2A-OT	1980				67	ICOLD	
	Churchrock, New Mexico, United Nuclear	WR	E	11	370,000	1A-FN	16-Jul-79	370,000	110		173	ICOLD, Wikipedia, Rico	
	Union Carbide, Uravan, Colorado, USA	US	T	43		2A-SI	Mar-79				172	ICOLD	
	Incident No. 1, Elliot, Ontario, Canada	WR	E	9		3-	1979				35	ICOLD	
	Suncor E-W Dike, Alberta, Canada	WR	MW	30		2A-SI	1979				118	ICOLD	
	Arcturus, Zimbabwe	US	T	25	1.7-2.0 Mt	1A-OT	31-Jan-78	39,000	0.3	1	185	ICOLD, WISE, Rico	
	Mochikoshi No. 1, Japan (1 of 2)	US	T	28	480,000	1A-EQ	14-Jan-78	80,000	8	1	84	ICOLD, WISE, Rico	Dam failure due to earthquake
	Norosawa, Japan	DS		24	225,000	2B-EQ	14-Jan-78				90	ICOLD	
	Hirayama, Japan	DS		9	87,000	2B-EQ	1978				56	ICOLD	
	Mochikoshi No. 2, Japan (2 of 2)	US	T	19		1A-EQ	1978	3,000	0.15		85	ICOLD, Rico	dam failure due to aftershock
	Syncrude, Alberta, Canada	CL	T			2A-FN	1978				120	ICOLD	
	Madison, Missouri, USA	WR	E	11		1A-OT	28-Feb-77				74	ICOLD	
	Homestake, N. Mexico, USA	US	T	21		1A-ST	Feb-77	30,000			59	ICOLD	
	Pit No. 2, Western	US	T	9		1A-SI	1977				96	ICOLD	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Unidentified, Hernando, County, Florida, USA	CL	E	6		2A-FN	1977				162	ICOLD	
	Western Nuclear, Jeffrey City, Wyoming, USA #2					1A-SI	1977	40			180	ICOLD	
	Kerr-McGee, Churchrock, New Mexico, USA	WR	E	9		1A-FN	Apr-76				64	ICOLD	
	Zlevoto No. 4, Yugoslavia	US	T	25	1,000,000	1A-SI	Mar-76	300,000			184	ICOLD, WISE	
	Dashihe. China	US		37		2A-EQ	1976				36	ICOLD	
	Unidentified, Idaho, USA	DS	E	34		2A-SI	1976				149	ICOLD	
	Cadet No. 2, Montana,	CL	E	21		2A-SI	Sep-75				18	ICOLD	
	Madjarevo, Bulgaria	US	T	40	3,000,000	1A-ST	1-Apr-75	250,000			219	ICOLD	
	Carr Fork, Utah, USA			10		1A-ST	Feb-75				22	ICOLD	
	Dresser No. 4, Montana,	CL	E	15		1A-FN	1975				40	ICOLD	
	Keystone Mine, Crested Butte, Colorado, USA					1B-U	1975				65	ICOLD	
	Mike Horse, Montana, USA	US	T	18	750,000	1B-OT	1975	150,000			79	ICOLD	
	PCS Rocanville, Saskatchewan, Canada	US	T	12		3-	1975				92	ICOLD	
	Unidentified, Green River, Wyoming, USA	WR	E	18		3-	1975				161	ICOLD	
	Heath Steele main dam, Brunswick, Canada	WR	R,E	30		2A-FN	1975				186	ICOLD	
	Bafokeng, South Africa	US	T	20	13,000,000	1A-SE	11-Nov-74	3,000,000	45	12	7	ICOLD, WISE, Rico	
	Golden Gilpin Mine, Colorado, USA			12		1B-U	Nov-74				50	ICOLD	
	Deneen Mica Yancey County, North Carolina, USA	US	CST	18	300,000	1A-SI	Jun-74	38,000	0.03		37	ICOLD	
	Silver King, Idaho, USA	DS	E	9	37,000	1A-OT	16-Jan-74	6,000			109	ICOLD	
	Galena Mine, Idaho, USA #2	US	MW	9		1A-OT	15-Jan-74	3,800	0.61		49	ICOLD, Rico	
	Berrien, France	US	R	9		1A-SE	1974				10	ICOLD	
	GCOS, Alberta, Canada	US	T	61		2A-SI	1974				47	ICOLD	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Unidentified, Mississippi, USA #2	US	T	20		2A-FN	1974				153	ICOLD	
	Unidentified, Canaca, Mexico	US	T	46		1A-OT	1974				159	ICOLD	
	Ray Mine, Arizona, USA inc #2	US	T	52		2A-SI	5-Feb-73				101	ICOLD	
	(unidentified), Southwestern USA	US	E	43	500,000	1A-SI	1973	170,000	25		169	ICOLD, WISE, Rico	noted as "Southwestern US" in WISE
	Earth Resources, N M,	US	T	21		1A-OT	1973				41	ICOLD	
	Ray Mine, Arizona, USA	US	T	52		1A-SI	2-Dec-72				100	ICOLD	
	Buffalo Creek, West Virginia, USA					1A	26-Feb-72	500,000	64.4	125	Table 1	ICOLD, WISE, Rico	Tailings traveled 27 km downstream, 125 people lost their lives, 500 homes were destroyed. Property and highway damage exceeded $65 million
	Galena Mine, Idaho, USA	US	E	14		2A-ER	1972				48	ICOLD	
	Cities Service, Fort Meade, Florida, phosphate					1A	3-Dec-71	9,000,000	120		31	WISE, Rico	
	Pinchi Lake, BC, Canada	WR	E	13		2A-ER	1971				95	ICOLD	
	Western Nuclear, Jeffrey City, Wyoming, USA					1A-ST	1971				181	ICOLD	
	Mufulira, Zambia			50	1,000,000	1A-MS	Sep-70	68,000		89	88	ICOLD, WISE	Saturated slime tailings deposited in a TSF #3 over subsidence feature flowed into an underground mine killing 89 miners.
	Maggie Pye, United Kingdom, clay	US	T	18		1A-SI	1970	15,000			75	ICOLD, WISE	
	Park, United Kingdom	WR	T	3		1A-OT	1970				93	ICOLD	
	Portworthy, United Kingdom	DS	R	15		1A-ST	1970				97	ICOLD	
	Unidentified, Mississippi, USA	US	T	15		1A-OT	1970				152	ICOLD	
	Williamsport Washer, Maury County, Tennessee, USA			21		1A-U	1970				182	ICOLD	
	Bilbao, Spain					1A-SI	1969	115,000	0.035	?	15	ICOLD, WISE	
	Monsanto Dike 15, TN,	DS	E	43	1,230,000	2A-SE	1969				86	ICOLD	
	Stoney Middleton, UK					1A-SI	8-Feb-68				217	ICOLD	
	Hokkaido, Japan	US	T	12	300,000	1A-EQ	1968	90,000	0.15		57	ICOLD, WISE, Rico	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Agrico Chemical, Florida, USA					1A-U	1968				1	ICOLD	
	IMC K-2, Saskatchewan, Canada	US	T	30		3-	1968				60	ICOLD	
	Climax, Colorado, USA					1A-U	2-Jul-67	12,000			33	ICOLD	
	Mobil Chemical, Fort Meade, Florida, phosphate					1A	1-Mar-67	2,000,000			83	ICOLD, WISE	250,000 m3 of phosphatic clay slimes, 1.8 million m3 of water. Spill reaches Peace River, fish kill reported
	Unidentified, United Kingdom	DS		20		1A-SI	1967				144	ICOLD	
	Unidentified, United Kingdom #3	DS	MW	14		2A-SI	1967				145	ICOLD	
	Unidentified, United Kingdom #2	DS	E	30		2A-SE	1967				146	ICOLD	
	Alberfan, Wales						21-Oct-66	112,000		144		Wikipedia	Coal tip (waste rock pile) failure
	Mir mine, Sgorigrad, Bulgaria	US	T			1A-U	1-May-66	450,000	8	488	81	ICOLD, WISE	Tailings wave traveled 8 km to the city of Vratza and destroyed half of Sgorigrad village 1 km downstream, killing 488 people.
	Williamthorpe, UK		MW			1A-OT	24-Mar-66				183	ICOLD	
	Unidentified, Texas, USA	US	T	16		1A-SE	1966	130,000			154	ICOLD, WISE	
	Gypsum Tailings Dam (Texas, USA)	UP		11	7,000,000	1A-SE	1966	85,000	0.3			WISE, Rico	Summary of Research on Analyses of Flow Failures of Mine Tailings Impoundments, J. K. Jeyapalan, J. M. Duncan, and H. B. Seed
	Derbyshire, United Kingdom	DS		8		1B-FN	1966	30,000			38	ICOLD	
	Williamthorpe, UK #2					1A-FN	1966				216	ICOLD	
	Tymawr, United Kingdom Inc#2			12		1A-OT	29-Mar-65				125	ICOLD, WISE	
	Bellavista. Chile	US	T	20	450,000	1A-EQ	28-Mar-65	70,000	0.8		12	ICOLD	The tailings failures of March 28, 1965, were from La Ligua, Chile, earthquake. This accounts for a significant part of the large number of earthquakes in the period of 1960-1970. About half of the failed dams were abandoned, and half were located at operating mines. (see Villavicencio et al, 2014)
	Cerro Blanco de Polpaico, Chile	WR	R	9		2A-EQ	28-Mar-65				26	ICOLD	
	El Cerrado, Chile	US	T	25		2B-EQ	28-Mar-65				42	ICOLD	
	El Cobre New Dam	DS	CST	19	350,000	1A-EQ	28-Mar-65	350,000	12		43	ICOLD, WISE	
	El Cobre Old Dam	US	T	35	4,250,000	1A-EQ	28-Mar-65	1,900,000	12	>200	45	ICOLD, WISE, Rico	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Hierro Viejo, Chile	US	T	5		1A-EQ	28-Mar-65	800			55	ICOLD	
	La Patagua New Dam,	US	T	15		1A-EQ	28-Mar-65	35,000	5		69	ICOLD, Rico	
	Los Maquis No. 1	US	T	15		2B-EQ	28-Mar-65				70	ICOLD	
	Los Maquis No. 3	US		15	43,000	1A-EQ	28-Mar-65	21,000	5		71	ICOLD, Rico	
	Ramayana No. 1, Chile	US	T	5		1A-EQ	28-Mar-65	150			99	ICOLD	
	Sauce No. 1, Chile	US	T	6		2A-EQ	28-Mar-65				104	ICOLD	
	Sauce No. 2, Chile	US	T	5		2B-EQ	28-Mar-65				105	ICOLD	
	Sauce No. 3, Chile	US		5		2B-EQ	28-Mar-65				106	ICOLD	
	Sauce No. 4, Chile	US	T	5		2B-EQ	28-Mar-65				107	ICOLD	
	Cerro Negro No. (1 of 5)	US	T	46		2B-EQ	28-Mar-65				27	ICOLD	Cracking due to EQ
	Cerro Negro No. (2 of 5)	US	T	46		2B-EQ	28-Mar-65				28	ICOLD	Cracking due to EQ
	Cerro Negro No. (3 of 5)	US	T	20	500,000	1A-EQ	28-Mar-65	85,000	5		29	ICOLD WISE, Rico	Dam failed due to EQ
	El Cobre Small Dam	US	T	26	985,000	2B-EQ	28-Mar-65				46	ICOLD	
	American Cyanamid, Florida #2					1A-U	1965				4	ICOLD	
	N'yukka Creek, USSR	WR	E	12		2A-FN	1965				89	ICOLD	
	Unidentified, Idaho, USA	DS	E	18		2A-SI	1965				150	ICOLD	
	Alcoa, Texas, USA			19	4,500,000	1A-U	Oct-64				2	ICOLD	
	Utah construction, Riverton, Wyoming, USA					2A-OT	16-Jun-63				174	ICOLD	
	Mines Development, Edgemont, South Dakota, USA					1A-U	11-Jun-62	100			80	ICOLD	
	Huogudu, Yunnan Tin Group Co., Yunnan	US				1A	1962	3,300,000	4.5	171		Wei	
	American Cyanamid, Florida					1A-U	1962				3	ICOLD	

COLOR CODE	MINE/PROJECT & LOCATION	DAM TYPE	DAM FILL MATERIAL	DAM HEIGHT (meters)	STORAGE VOLUME (cu. meters)	ICOLD TYPE	INCIDENT DATE	RELEASE VOLUME (cu. meters)	RUNOUT (km)	DEATHS	Source Color Code	SOURCES	NOTES
	Unidentified, Peru					1A-EQ	1962				135	ICOLD	
	Union Carbide, Maybell, Colorado, USA					1A-U	6-Dec-61	280			171	ICOLD	
	Tymawr, United Kingdom					1A-U	Dec-61				124	ICOLD	
	Lower Indian Creek, MO,	US	E			2A-SI	1960				72	ICOLD	
	Union Carbide, Green River, Utah, USA					1A-OT	19-Aug-59	8,400			170	ICOLD	
	Grootvlei, South Africa	US	T			1A-SI	1956				54	ICOLD	
	Unidentified, Peace River, Florida, USA 3/52	WR	E	8		1A-SI	Mar-52				168	ICOLD	
	Unidentified, Alfaria River, Florida, USA	WR	E	8		1A-SI	Feb-52				156	ICOLD	
	Unidentified, Peace River, Florida, USA 9/51	WR	MW	6		1A-SE	Sep-51				165	ICOLD	
	Unidentified, Peace River, Florida 7/51	WR	MW	30		1A-SE	Jul-51				166	ICOLD	
	Unidentified, Peace River, Florida, USA2/51	DS	E			1A-SE	Feb-51				167	ICOLD	
	Kimberley, BC, Canada, iron	US	T			1A-SI	1948	1,100,000			66	ICOLD	
	Castle Dome, Arizona, USA	US	T			1A-SE	29-Sep-47	150,000	0.1		25	ICOLD	
	Hollinger, Canada	US	T	15		1A-FN	1944				58	ICOLD	
	Captains Flat Dump 3, Australia		T			1A-U	1942	40,000			20	ICOLD	
	Kennecott, Utah, USA	US	T			1A-FN	1942				63	ICOLD	
	Kennecott, Garfield, Utah, USA	US	T			1A-SI	1941				62	ICOLD	
	St. Joe Lead, Flat Missouri, USA	US	T	15		1A-OT	1940				115	ICOLD	
	Captains Flat Dump 6A, Australia	US	T			1A-SI	1939				21	ICOLD	
	Simmer and Jack, South Africa	US	T			1A-SI	1937				110	ICOLD	
	Barahona, Chile	US	CST	61	20,000,000	1A-EQ	Oct-28	2,800,000			9	ICOLD	
	Unidentified, South Africa					1A-U	1917				136	ICOLD	

APPENDIX 2

Technical Documentation on Canonical Correlation Analysis

TECHNICAL DOCUMENTATION ON CANONICAL CORRELATION ANALYSIS

Canonical Correlation Analysis (CCA)

Canonical correlation considers the relationship between two data sets one normally considered a "criteria" data set the other and "explanatory" data set. For our CCA analysis the criterion data set (Y1) were the Very Serious Failure and Serious Failures. The explanatory data set (Y2) were the three mining metric variables shown to have the highest correlation with these failure categories copper ore production (Cu prod), copper grade (Cu grade), and copper cost to produce (Cu cost).

Table A2.1 - Input Data Set

Decade	Very Serious Failures	Serious Failures	Other Failures	Other Accident	Non-Dam Failures	All Failures	Cu prod (K tonnes)	Cu grade (%)	Cu cost $/tonne	Cu price $/tonne
1940 – 49	0	0	5	0	0	6	2,545	1.52	$35	$3,633
1950 – 59	1	0	7	0	0	7	3,680	1.21	$48	$5,076
1960 – 69	3	4	25	17	2	51	5,004	1.10	$55	$5,112
1970 – 79	4	8	23	15	3	53	7,445	1.01	$38	$5,895
1980 – 89	5	9	22	14	4	54	10,575	0.95	$20	$3,871
1990 – 99	9	9	10	3	1	32	16,437	0.93	$15	$3,292
2000 – 09	7	8	5	1	0	21	23,658	0.85	$20	$4,256
	======	======	======	=======	=======	======	======	=====	======	=======
Total/Ave	29	38	97	50	10	224	69,344	1.54	$33	$4,448

Abbreviations:

Cu Price = Copper price ($/tonne)
Cu Prod Cost = Cost to produce copper concentrate from copper ore, including waste disposal ($/tonne)
Cu Grade = grade of copper in the ore (%)
Cu Prod = copper ore production (thousand metric tonnes)
Other Failures = tailings dam failures and incidents other than Serious or Very Serious Failures
Serious Failures = Serious tailings dam failures
Very Serious Failures = Very Serious tailings dam failures

Sources: USGS (Metal Statistics) 2014, Schodde 2010, ICOLD 2001, WISE 2015 & additional

Development And Vetting Of Input Data

These final selections were based on a rigorous and thorough exploration of the structure of the data within each set and of the inter-relationships among data elements. After settling on the above data set it was vetted against two criteria for proper use and meaningful interpretation of CCA: Multivariate Normality and Multicollinearity.

We had pre-determined CCA to be the best multivariate analysis technique for our consideration of how the "Mining Metric" affects TSF failure frequency and severity globally. We were not looking at this relationship on a time series basis but on a criteria and explanatory basis for which CCA was specifically developed. CCA is used mostly for looking at whether and how intentional or known environmental conditions or interventions affect a given set of observed conditions. (E.g. and more typically, whether the elements of a diet and exercise program, as a program, have more positive effect on measures of health and which elements are most strongly related to the desired or expected outcome.) At least one major economic study (Malacarne 2014) published in the Mathematica

Journal also employed CCA. That study explored whether and to what extent behavior of the major stock exchanges of developed nations influenced the behavior of the exchanges of developing nations.

CCA is perfectly suited to our study because although price is the fixed element against which all mines must perform, the other elements of the Mining Metric are subject to miner control and or have great variability one mine to another within the expressed averages, including how much production to undertake at a given head grade and mine specific cost of production, and how much cash flow is available for nonrevenue generating parts of the operation like waste and waste water management.

Development Of Input Variables

The main defining criteria for severity classifications are apparent on a sort by Release Volume (column L) and Run Out (column M) (See Appendix I), or even a visual inspection. The category Very Serious Failures has had clarity in all analysis from the outset in its relationship to the key Mining Metric variables, and much stronger alone than in combinations we experimented with. Similarly, combinations of coding for other incidents didn't have the clarity we finally found in these final 5 major failure groups. Among these 5 groups (classifications) as shown in the correlation matrix in Table 3.1 only the two high severity codes had significant correlations with Mining Metric variables.

Similarly with the Mining Metric variables we found that the original raw data had greater clarity than any combinations we formulated. For example, on noting the lower correlation of price with failures variables, we created a variable called "price cycle" that coded each decade on the basis of length of trend up or down. Since cumulative production is a surrogate for the exponential growth in global accumulated tailings volume we initially focused on that but found that cumulative production had consistently lower correlations with any coding of failure categories, and so settled on using production as reported by the USGS metal statistics. We tried to improve correlations with various other formulations. But in all cases the actual raw measurements of cost, grade and production were found to have the highest correlations with high severity failures events.

We also had explored an "all metals" basis in lieu of using Cu only and found that no combination of all metals had the same strength of correlation as Cu production alone. (Possibly because Cu production so closely tracks Global GDP). USGS Metal Statistics (2014) includes price, but there were no other comparable sources for average head grade or average production costs. Only Cu afforded the possibility of looking at the interrelationships over the entire century 1910-2010.

For almost any analysis there were too many empty cells for a complete Y1 and Y2 set prior to 1940. Therefore we ended up with a workable data set of only two Y1 variables and three Y2 variables for only 7 decades out of the 10 in the century. At the outset, therefore, we knew that our workable data set was much smaller than what is normally considered the minimum for CCA, and that that would limit the statistical significance of conclusions, but not preclude a meaningful glimpse into the relational behavior of the two data sets.

Appropriate Aggregation Level of Failure Data

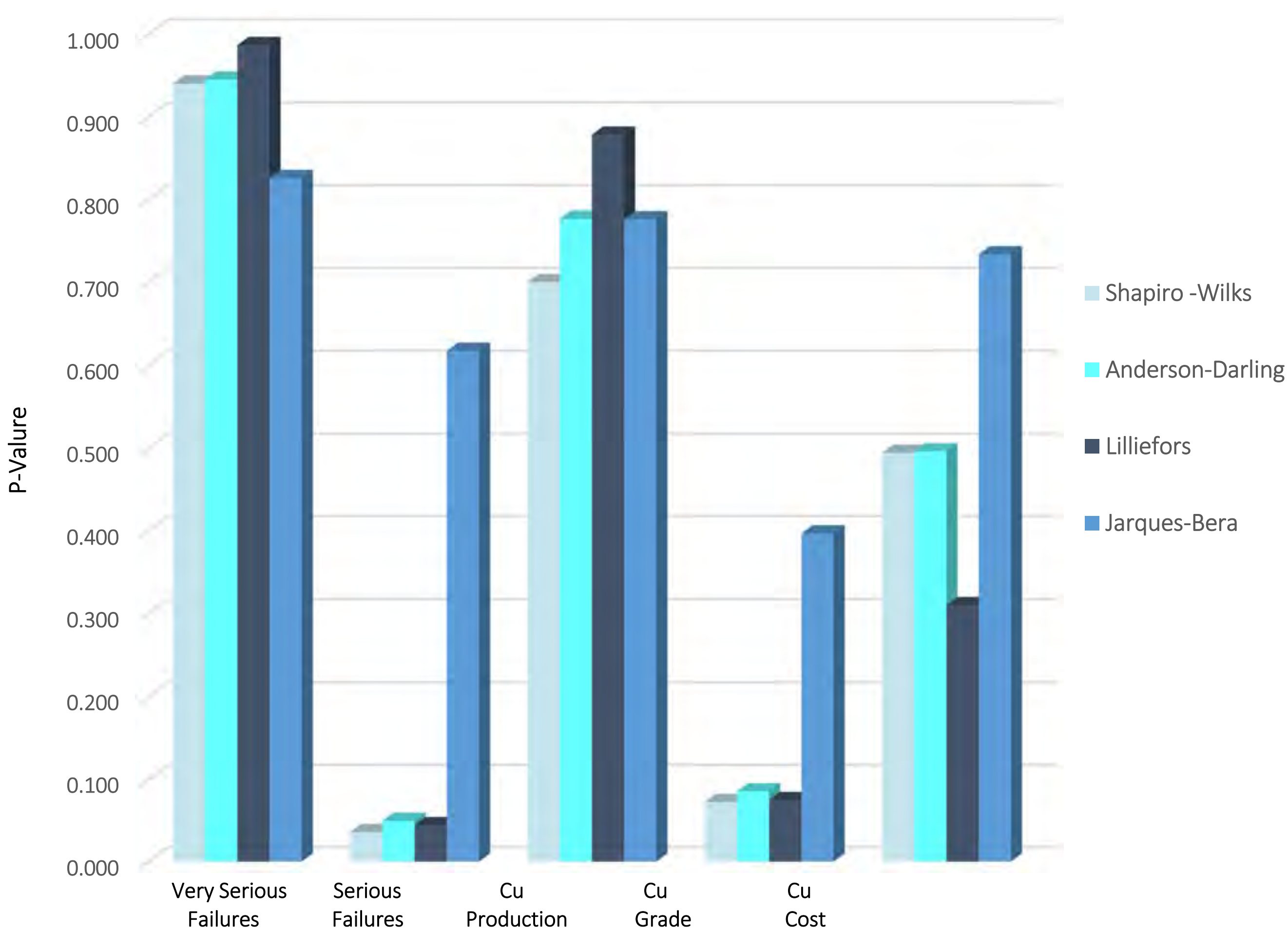
To determine the most appropriate level of aggregation for the failure data sets we looked at aggregations by 1, 2, 5 and 10 years building from the earliest year, 1910. The decade 1910-1920 is the earliest recorded ICOLD TSF incident. We found that the clarity of inter relationships was not apparent at aggregations below 5 years and was most clear at aggregations by decade.

Ideally, there should be 20 observations for each variable which would have required aggregations of 3 years or less. This is also true of the U.S. Census or any other phenomenon that looks at small incremental changes or incidents over a long period of time and the interrelationship with other inter-census changes. These changes would not be apparent or meaningful at smaller levels of aggregation as the many elements of population change (age, ethnicity, household size) have constant small changes day-by-day, month-by-month, which don't reveal the magnitude of net effect or net change until a meaningful level of aggregation is established. Ten years happens to be the apparent optimum level of aggregation for analysis of frequency and severity of TSF failures and reportable incidents.

VETTING OF INPUT DATA SET ON REQUIREMENTS FOR CCA

The proper use of CCA for descriptive analysis requires no assumptions of distribution. To test the significance of the relationships between canonical variates, however, the data should meet the requirements of multivariate normality (MVN). We were not able to conduct a full multivariate normality as it was not an option in XLSTAT©. The normality of each variable within the data set is not a proof of MVN, but all elements of a data set that does meet the requirements of MVN must meet univariate tests of normality. We therefore used the results of univariate tests on each of the 5 input variables as an approximation of MVN as did Malacarne (2014). XLSTAT© automatically gives output for 5 different normality tests and is presented in Figure A2.1, below: P values at 95% confidence intervals are presented for each test on each variable. (The higher the P value the more likely the sample/observation set is drawn from a population with a normal distribution.) The alpha level was 0.05 (95% confidence limits). The closer to 0.05 alpha value the P value is the less certainty that the data set is from a population with a normal distribution. Each test involves different assumptions and approaches to testing for a normal distribution.

Figure A2.1 Tests of Normality
Comparisons on Major Measures By Variable



These results are being presented as a point of interest to get some insight to the data set. All of these measures are known to be robust with very small data sets and normally 20 is the smallest data set they should be performed on. Interesting and not unexpected to note that all 5 variables satisfied only the Jarques-Bera that is most often the case with econometric data sets. Jarques-Bera, alone requires no known mean or standard deviation and is based on skewness and kurtosis. It is interesting to note that "Serious Failures" and "Cu Grade" satisfied the criteria for normality only on the Jarques-Bera. In the case of "Serious Failures" that could be due to its "curvature". (See Figure 3.2) In the case of Cu Grade it may be due to the small difference min to max. Despite the results, this is not conclusive of MVN but strongly suggests that and supports that our use of CCA for exploration is reasonable.

Multicollinearity must not exist for meaningful use and interpretation of CCA Each data set was also tested via principal Component Analysis for Multicollinearity and the eigenvalues for each were very high, 1.880 for the failures data set accounting for 94.013 % of variability and 2.546 for the mining metric data set accounting for 84.8% of variability. Again there is a tendency to robustness in small data sets with very strong linearity. We are concluding only that the data set seems to satisfy the requirement for no Multicollinearity.

All of these results support that CCA is a suitable analytic tool for this Y1, Y2 data set and that the results can be meaningfully interpreted, albeit with acknowledged limitations on affirming statistical significance.

Table A2.2 – Failures Data Eigenvalues

	F1	F2
Eigenvalue	1.880	0.120
Variability (%)	94.013	5.987
Cumulative %	94.013	100.000

Table A2.3 – Mining Metric Data Set Eigenvalues

	F1	F2	F3
Eigenvalue	2.546	0.377	0.077
Variability (%)	84.859	12.570	2.571
Cumulative %	84.859	97.429	100.000

Our aim was not statistical significance, but a better understanding of the nature and structure of the relationship between the high severity failures and the mining metric variable affecting all mines and all miners. CCA offered that and is particularly well suited to exploration of relationships within complex systems and complex multi causal effects.

TSF failures resist any efforts to definitively map what specific combinations of events will result in failure, but we can meaningfully explore the contribution of various elements.

Our data set of "causes" most often associated with failure is itself raggedly incomplete and not systematically recorded for every failure. CCA allows analysis of the relationships between any two sets of system known to be much more complex than just the effects studied through CCA. It allows an open exploration of inter relationships and their intensity without in any way discounting other factors that may contribute as much or more to both likelihood of failure and severity of failure.

OUTPUTS OF CCA

Canonical Correlation Analysis (CCA) is most usually and almost universally defined as "the problem of finding two sets of basis vectors, one for data set Y1 and the other for data set Y2, such that the correlations between the projections of the variables onto these basis vectors are mutually maximized."

CCA seeks a pair of linear transformations, one for each of the sets of variables such that when the set of variables are transformed the corresponding co-ordinates are maximally correlated. The linear transformations are synthetic variables. One "synthetic variable" or canonical variate is create for each data set.

CCA is in some respects similar in principal to dimensional analysis in engineering employed to statistically explain or explore the complex relationships producing observed measurements. CCA similarly “discovers” the relationships that may not otherwise be apparent in univariate correlation analysis or which may be understated or not detected at all in univariate analysis (because of interrelationships within and between the two sets)

UNIVARIATE CORRELATION MATRIX

The univariate correlation matrix is a standard CCA output and presents the relationships in the entire data set, and is used to assess both the degree of independence and the degree of individual variable to variable relationships across all variables in the selected arrays Y1 (the severity of failure array) and Y2 (the Mining Metric array). These values are the same as those shown in Table 3.1 for the full original data set. This data set was pre-selected for the CCA for the strength of the correlations between the two failure severity classes (Y1) and the three selected mining metric variables (Y2).

Table A2.4 – CCA Output Correlation Matrix

		Y1		Y2		
		Very Serious Failures	Serious Failures	Cu prod	Cu cost	Cu grade
Y1	Very Serious Failures	1	0.880	0.860	-0.788	-0.794
	Serious Failures	0.880	1	0.720	-0.682	-0.884
Y2	Cu prod	0.860	0.720	1	-0.782	-0.756
	Cu cost	-0.788	-0.682	-0.782	1	0.497
	Cu grade	-0.794	-0.550	-0.756	0.497	1

EIGENVALUES

The principal output of a canonical correlation analysis are the canonical functions (variates) which seek to maximize explained variability between the two arrays (Y1 and Y2). Each function produced is an equation (similar to the equations created in regression analysis) but instead of explaining the relationships in terms of causality, it seeks to define the dimension (strength) of the relationship between (or in larger data sets among) the arrays. Essentially it asks are these arrays independent of one another, or does there appear to be an influence of the two arrays on one another. As many canonical functions are produced as there are variable sets

The first exploration of these canonical functions is the eigenvalue which measures how much variability is explained by each of the canonical functions. The closer the eigenvalue is to zero the less likely the two arrays form a diagonal matrix, i.e. have a linear correlation to one another which might therefore be suitable for linear modeling (regression analysis).

Table A2.5 – Eigenvalues

	FAILURES DATA EIGENVALUES	
	Canonical Function 1	Canonical Function 2
Eigenvalue	0.903	0.528
Variability (%)	63.1	36.9
Cumulative %	63.1	100.000

In this case the Eigenvalue for the first canonical function, F1, 0.903 strongly indicates a diagonal matrix. F1 explains explained 93.9% of the total variability between the two arrays indicating a very strong diagonal matrix. The second function, F2, calculated to be maximally independent of the first, in our data set also contributes to explaining 36.9% of the relationship between the two arrays.

We would expect any two data sets with similar within set patterns to produce very high eigenvalues but this FI result is higher than any produced from randomly generated arrays with similar slope and range for each variable. So this does add to our understanding of the strength of the linear relationship between Y1 and Y2.

WILKS LAMBDA

Wilks' Lambda is a test of the null hypothesis that the data sets are independent of one another as measured via the canonical coefficients. The lower the Wilk's Lambda, the less likely that the data sets Y1 and Y2 are independent. The following results means it is unlikely that the two data sets are independent of one another.

Table A2.6 – Wilks' Lambda Test

	Lambda	F	DF1	DF2	Pr > F
F1	0.046	2.451	6	4	0.202
F2	0.937				

F-Value

The value of the F approximation (a probability distribution) for testing the significance of the Wilks' Lambda corresponding to this row and those below it. If F is an approximation, as here, it is generated as appropriate to the test. Similar F values were XLSTAT generated for the actual (4.6) and the control (4.58) data sets. The first F-value tests the significance of the 1st and 2nd canonical correlations.

DF1

The numerator degrees of freedom of the above F-ratio.

DF2

The denominator degrees of freedom of the above F-ratio.

PR>F (Probability Level)

This is the probability value for the above F statistic. A value near zero indicates a significant canonical correlation. A cutoff value of 0.05 or 0.01 is often used to determine significance at the 95%h of 99% level.

This result is below a 95% confidence level (0.05) but is still strong (92%) I.e., if we accepted the null hypothesis that the two data sets are independent of one another there is a 92% chance we'd be wrong.

Again any data sets with similar variable ranges and slopes would also produce similarly strong results, but several trials with made up data sets did not yield results as strong as the actual data sets. For example, the data set in Table A2.5 below produced lower eigenvalues and higher Wilks Lambdas than the actual data (although the Wilks result in the control set is significant at a higher level than the actual data set).

The data set in Table A2.5 has very similar slope and pattern to the actual failures and mining metric data sets. The synthetic data are plotted in Figure A2.2.

The very high R-Squared as for the actual data set. The eigenvalue not as high and the Wilk's Lambda not as low.

The real data shows a strength of relationship that is not present in synthetic data sets with similar dimensionality and slope for each of the 5 variables.

Table A2.7 – Synthetic Data Set

Decade	Synthetic Very Serious Failures	Synthetic Serious Failures	Synthetic Cu Grade	Synthetic Production Cost	Synthetic Cu Production
1	46.8	49.95	70.14	66.0	50.00
2	39.0	42.18	65.13	52.8	51.55
3	31.2	57.72	46.76	24.2	53.15
4	46.8	43.29	33.40	17.6	54.80
5	54.6	53.28	31.73	13.2	56.49
6	54.6	62.16	30.06	8.8	58.25
7	62.4	57.72	20.04	6.6	60.05
8	54.6	65.49	18.37	6.6	61.91
9	70.2	61.05	15.03	4.4	63.83
10	62.4	69.93	5.01	4.4	65.81
11	70.2	68.82	3.34	6.6	67.85
12	62.4	69.93	1.67	11.0	69.95

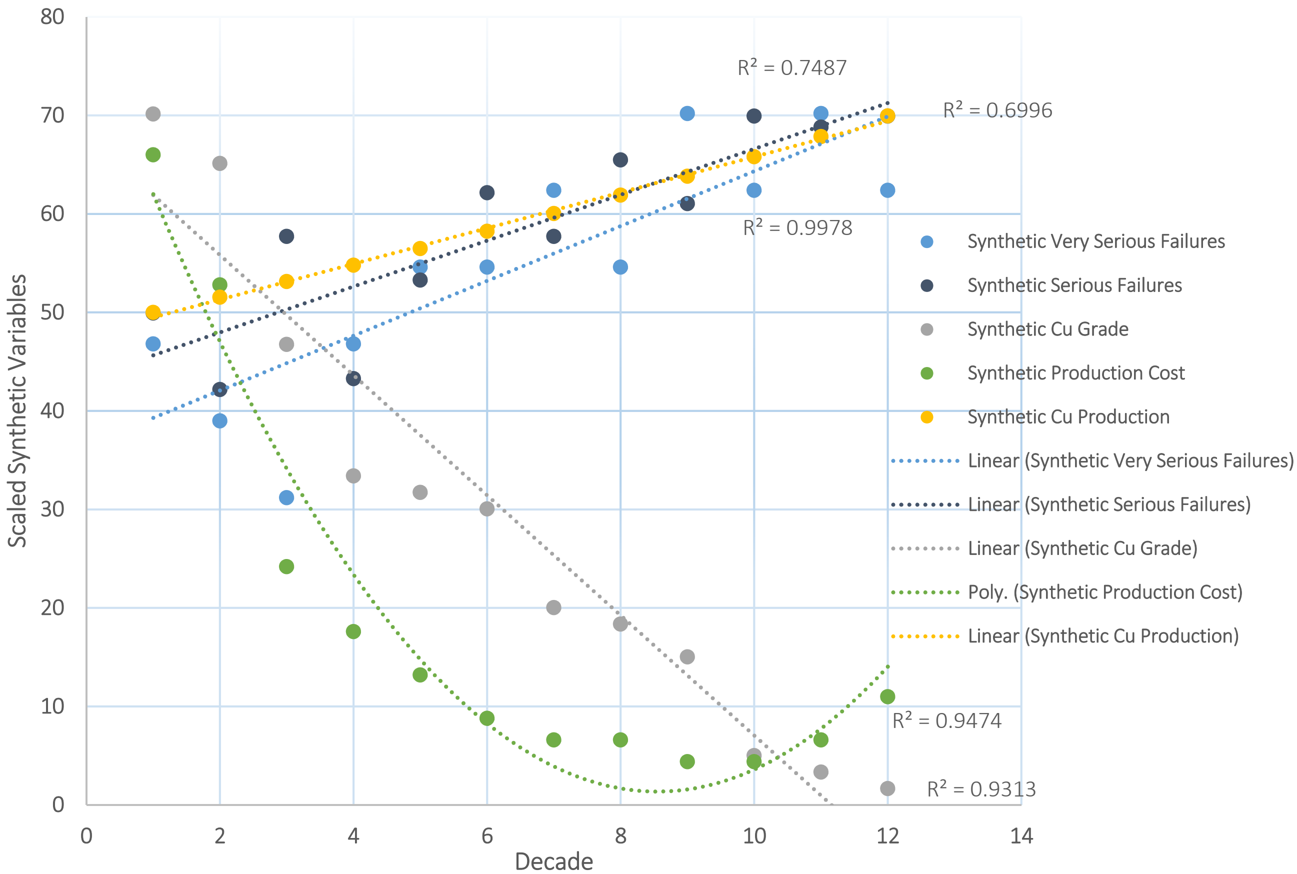
Table A2.8 – Synthetic Data Set Wilks' Lambda Test

	Lambda	F	DF1	DF2	Pr > F
F1	0.114	4.583	6	14	0.009
F2	0.932				

Table A2.9 – Synthetic Data Set Eigenvalues

	Canonical Function 1	Canonical Function 2
Eigenvalue	1.880	0.120
Variability (%)	94.013	5.987
Cumulative %	94.013	100.000

Figure A2.2 – Graph of Synthetic Values



Canonical Correlations

The canonical correlations (also called variates) are the two synthetic variables resulting from the projections of each data set onto a base vector maximizing the mutual variability between the two data sets. The result for each function, F1 and F2 describes the amount of variability accounted for. The higher the value the greater the amount of variability explained by the functions. Function F1 explained 95% of the variability.

Table A2.10 – Canonical Correlation Values

	F1	F2
Canonical Correlation	0.950	0.727
Eigenvalue	.903	0.528
Wilks' Lambda	0.046	0.472

CORRELATION BETWEEN F1 CANONICAL VARIATE AND DATA SET VARIABLES

The aim of CCA is to discover whether dimensions of relationship exist between y1 and y2 variables that were not apparent in the graphs, charts and univariate analysis vis-a-vis one to one correlations. The correlations are shown below between both correlations (F1 and F2), and each variable in each data set, Y1 and Y2. They reveal a stronger influence of grade and cost to produce and reaffirmed the primary dominant relationship with production volume on both categories of failure severity. It also brought out stronger relationships in general between Serious Failures and the Mining Metric variables than were revealed in univariate and graphic analysis. The relationship between Serious Failures and the mining metric may be via cost of production.

Very Serious Failures had a much stronger and opposite correlation with F2 than did Serious Failures, - 0.388 v. - 0.096. The main component in F2 is ore production (-0.588) with cost also strong, 0.450.

In F1 which is much more strongly correlated with Serious Failures, grade is the principal element, 0.929. (While the second variate, F2 does not have the Wilks and Eigen Values of F1, it does it does illustrate that serious failures is a distinctive and separate failure severity group despite its many commonalities with very serious failures. As the possibility of larger data sets grow going forward (i.e. more information from 2000 onward) it may be possible to explore those differences more fully.

The first canonical variate, F1, had very strong correlations with all variables in each of the two data sets (Y1, failures and Y2, mining metric elements. Both of the failure variables and production volume had very strong negative correlations with F1: -0.922, -0.995. Cu Ore Production (-0.802). Cu Cost (0.755) and Cu Grade (0.929) were also highly correlated with F1. F1 is a therefore a nearly complete expression of the very strong relationship between the two data sets with each of the mining metric elements.

Table A2.9 - Input and Canonical Variable Correlations

Correlations between input variables and canonical variables (Y1):

	F1	F2
Very Serious Failures	-0.922	-0.388
Serious Failures	-0.995	0.096

Correlations between input variables and canonical variables (Y2):

	F1	F2
Cu Production	-0.802	-0.558
Cu Cost	0.755	0.072
Cu Grade	0.929	0.368

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NCSS Statistical Software "Canonical Correlation Analysis" Accessed March 27 at http://ncss.wpengine.netdna-cdn.com/wp-content/themes/ncss/pdf/Procedures/NCSS/Canonical_Correlation.pdf

http://faculty.arts.ubc.ca/dwhistler/325ClassNotes/chapNorTest.pdf

APPENDIX 3

Documented TSF Very Serious Natural Resource Losses

1990 - 2010

Documented TSF Very Serious Natural Resource Losses 1990 – 2010

TSF Failure	Year	Original Currency (Millions)	Failure Year M US$	2014 M US$	Ore	Release (M m^3)	Run Out (km)	Deaths	Source
Kingston Fossil Plant, Harriman, Tennessee, USA	2008	US 1,200	$1,200	$1,300		5.4	4.1		http://www.sourcewatch.org/index.php/TVA_Kingston_Fossil_Plant_coal_ash_spill
Taoshi, Linfen City, Xiangfen, Shanxi Province, China	2008	US 1,300	$1,300	$1,429	Fe	0.19	2.5	277	Wei, Yin, Wang Ling,Wan(2012), http://wmr.sagepub.com/content/31/1/106.full.pdf+html
Baia Mare, Romania	2000	US 179	$179	$246	Au	0.1	5.2		(1) http://www.wise-uranium.org/mdafbm.html (2) http://viso.jrc.ec.europa.eu/pecomines_ext/docs/bmtf_report.pdf
Los Frailes, Spain	1998	EU 275	$301	$437	Zn/Cu/ Pb	4.6	5		http://www.wise-uranium.org/mdaflf.html
Marinduque Island, Philippines	1996	P 180 + US 114	$123	$185	Cu	1.6	27		(1) http://www.slideshare.net/no2mininginpalawan/major-tailings-dam-disasters-in-the-philippines-alyansa-tigil-mina-atm-april-2011-7819384Philippines (2) http://newsinfo.inquirer.net/479345/marinduque-folk-lose-case-vs-mine-firm (3) http://opinion.inquirer.net/63421/marinduque-is-pushed-to-the-wall (4) http://www.slideshare.net/jillentot/environmental-damages-and-health-hazards-caused-by-marcopper?related=1 (5) Bennagen, 1998
Omai, Guyana	1995	US 100	$100	$156	Au	4.2	80		(1) http://www.thefreelibrary.com/Cambior+Inc.+Announcement.-a055509330 (2) http://www.monitor.net/monitor/9-18-95/eyewitness.html (3) http://ejatlas.org/conflict/omai-gold-mine-tailings-dam-guyana (4) http://www.multinationalmonitor.org/hyper/issues/1995/11/mm1195_04.html
Merriespruit, South Africa	1994	R 100	$29	$46	Au	0.6	2	17	http://floodlist.com/africa/merriespruit-tailings-dam
	Average US$2014: $543			====== $3,799					

NOTES:

A. HISTORICAL CURRENCY CONVERTERS

(1) http://unix4.outcoursing.com/currency-converter/us-dollar-usd_zar-south-african-rand.htm/1994

(2) http://www.x-rates.com/historical/

2005-2015 selected currencies

(3) http://fxtop.com/en/currency-converter-past.php?A=275&C1=EUR&C2=USD&DD=01&MM=01&YYYY=1998&B=1&P=&I=1&btnOK=Go%21

Converts from any one currency to another for any given date 1953-2015

(4) http://www.usinflationcalculator.com/

Advances value of $US from any year from 1913 to any year up to 2015

B. DOCUMENTED TSF VERY SERIOUS NATURAL RESOURCE LOSSES

(1) **TAOSHI, LINFEN CITY, XIANGFEN COUNTY, SHANXI PROVINCE**

US2008 $1,300 million = US2014 $1,429 million

This failure released approximately "1.9 × 105 m^3 tailings. The tailings flowed as far as 2.5 km downstream and covered about 35 hectares of land. … The tailings destroyed many houses, caused 277 deaths, 33 injuries, and caused about US$ 1.3 × 10^7 in direct losses. The failure also resulted in very serious social impacts."

Source:
(a) http://wmr.sagepub.com/content/31/1/106.full.pdf+html

(2) **BAIA MARE**

US2000 $179 million = US2014 $246 million

Operated by AURUL, a joint-venture between Esmeralda Exploration of Australia and REMIN the Romanian state owned mining company.

"On Dec. 16, 2000, Tom Garvey, the head of a European Union task force investigating the spill said there is no doubt the mine was at fault and is responsible for the environmental disaster." No doubt whatever it was a direct result of a hundred tonnes plus of cyanide going into the Pau, the Somas and the Tisza River and killing everything in its wake," he said.

The investigation concluded that the accident was caused by the inappropriately designed tailings dams, the inadequate monitoring of the construction and operation of those dams and by severe - though not exceptional - weather conditions. (Australian Broadcasting Corporation Dec. 16, 2000) (1)

Excerpts from the Baia Mare International Task Force Investigation

"As a result, it is the conclusion of the BMTF that the accidents were caused:

- Firstly, by the use of an inappropriate design of the TMF;
- Secondly, by the acceptance of that design by the permitting authorities; and
- Thirdly, by inadequate monitoring and dam construction, operation and maintenance"(2)

"Furthermore there was a problem in the case of Baia Mare with the stability of the embankment walls themselves. This arose because the Baia Mare facility used a recognized technique of embankment or dam wall construction (called 'construction by operation') which called for the gradual deposition of tailings of sufficiently coarse grade on the starter walls to ensure stable and continuous growth of the height of the embankment walls.

However, the mix of tailings used did not have the ratio of coarse to fine grades stipulated in the design and, in addition, the hydrocyclones used to distribute the tailings within the pond could not operate in the very low temperatures experienced before the accident. As a result the embankment wall construction was interrupted at a critical time, leading to a reduction in the 'freeboard', and consequently to wall breaching and overflow." (2)

"In effect, these were two accidents waiting to happen, waiting for the necessary trigger of adverse weather conditions which was bound to come sooner or later." (2)

On July 11, 2000, the Hungarian Government lodged a $179 million compensation claim against Esmeralda Exploration. (1)

Sources:

(a) http://www.wise-uranium.org/mdafbm.html
(b) http://viso.jrc.ec.europa.eu/pecomines_ext/docs/bmtf_report.pdf

(3) **LOS FRAILLES**

EU1998 €275 million = US1998 $301.4 million = US2014 $437 million

Operated by Boliden Ltd. Sweden via subsidiary Boliden-Apirsa

On November 20, 2001, the Andalusian Government and the Spanish Environmental Ministry announced to sue for damages. Both Administrations have spent more than Pesetas 40,000 million (Euro 240 million / US$ 210 million) for the clean-up of the spill. (El País Nov. 21, 2001)

On December 14, 2001, Boliden Apirsa signed agreements with the Regional Government of Andalucía and with the workers council and unions regarding environmental restoration plans and severance payments. The mining company had presented a plan of environmental restoration and abandonment of the mine valued in 8,269 million pesetas (EUR 50 million / US$ 45 million). The workers council, however, estimated that at least an additional 5,000 million pesetas (EUR 30 million / US$ 27 million) were required. I.e. future work estimated by regional government of Andalusia at $72 million (beyond what was sent as of 11/21/2001)

In the agreement obtained, the Regional Government had to accept the payment with assets of the company for lack of sufficient funds available. But it reserved the right to claim from Apirsa's Swedish parent company Boliden Ltd any additional funds that might be required in the future. (El País Dec. 15, 2001)

The environmental group Ecologistas en Acción has decided to draw the case on the penal responsibility for the tailings dam failure before the Constitutional Court. (El País Feb. 1, 2002)

On April 23, 2002, the advisor of Environment, Fuensanta Coves, indicated that the legal services of the Regional Government are completing the statements of civil claims against Boliden-Apirsa, to demand a part of the funds used to repair the damages of the accident. The Andalusian Administration has invested more than 152 million Euros (around 25,000 million Pesetas) in the recovery, and it anticipates to spend another 10 million Euros in 2002. El País April 24, 2002) (i.e. total costs as of 2002 put at $162 EU)

On July 2, 2002, the Environmental Council of the Andalusian Government approved the initiation of civil actions against the mining company to try to recover part of the 152 million Euros (25,000 million pesetas) spent to decontaminate the affected zone. (El País July 3, 2002)

On July 31, 2002, the Environment Council of the Andalusian Government concluded the removal of the 10,000 cubic meters of muds that still were stored in the river basin of the Guadiamar. The Environment Council furthermore announced that it will come to the reforestation of the affected zone in October 2002. (El País August 1, 2002)

On August 2, 2002, the Council of Ministers imposed a penalty of 45 million Euros on Boliden, the highest ever by environmental damages in Spanish history. Nevertheless, the fine covers only about one sixth of the cleanup cost of 276 million Euros spent by the administrations so far. (El País / El Mundo, August 3, 2002)

Boliden announced it is not willing to pay a single cent. (ABCe August 5, 2002)

The Andalusian Government plans to impose another penalty of 86 million Euros on Boliden to recover the cost it has spent on the cleanup. (El País August 6, 2002)

Boliden claims damages from the Spanish construction company Dragados: Boliden's Spanish subsidiary Boliden Apirsa has filed a notice of litigation against Dragados y Construcciones S.A., a member of the construction company Dragados S.A., listed in Spain, in connection with the failure of the tailings dam at the Los Frailes mine, Spain, in 1998. Boliden´s claim against Dragados amounts to a minimum of **1 billion SEK (107 million Euro).** The formal claim will be presented to a Spanish court in October. (Boliden Sep 26, 2002)

On Nov. 16, 2002, the regional government of Andalusia filed a civil suit to recover from Boliden 89.8 million euros ($89.9 million) in damages and cleanup costs. (Reuters Nov. 22, 2002)

On Jan. 2, 2003, the Primera Instancia número 11 court of Seville rejected the civil demand of the regional government of Andalusia against Boliden. (ABCe Jan. 4, 2003)

The regional government of Andalusia now has decided to demand from Boliden recovery of 89.9 million euros in damages by the administrative route. (ABCe Nov. 5, 2003)

"As previously announced, Boliden's Spanish subsidiary Boliden Apirsa filed a notice of litigation against the Spanish company Dragados y Construcciones S.A. Now Boliden Apirsa has filed the final claim in a court in Madrid. Boliden's claim against Dragados amounts to around EUR 115 million." (Boliden Jan. 23, 2004)

Source:

(a) http://www.wise-uranium.org/mdaflf.html

(4) **OMAI**

US1995 $100 million = US2014 $156 million

Operator: Cambior, subsidiary Golden Star Resources in partnership with INVESCOR of Denver, via subsidiary Omai Mines Ltd in which Guyana Government had 4% interest.

Class Action Lawsuit for $2B dismissed against Cambior & claimants ordered by Guyana court to pay all defense costs of all named mining interests and their insurers. (3) The dismissal and general outcome viz a viz environmental damages is widely considered a failure of environmental justice. There has been no systematic accounting of actual damages by the Guyana Government or any NGO only the imposition of a $100 million fine.

"Several months before the disaster, the company told the government that because it had underestimated the amount of waste it would produce, it would need to build a second tailings dam and partly because of the cost would be unable to pay any royalties and taxes to the government until the year 2002, just three years before the mine's is expected to close. The news had reportedly caused dismay in government circles. As Omai is the largest open pit gold mine in South America, the government expected it to contribute substantially to its revenues." (2)

"The disaster only added fuel to an already difficult relationship. Instead of being a source of revenues, the mine is now a cause of more environmental expenditures for the government, whose foreign debt sometimes consumes as much as 70 percent of its tax revenues.

"There have been warnings of a disaster in the making for months. In March, the operators of the mine warned that disposal of the waste water was a problem, and prophetically suggested the mine might need to close in August if no other way was found to deal with the waste. A small spill occurred in May and in June the government announced an investigation into whether company plans to discharge effluent into the river were environmentally sound.

"Roger Moody, the Mining Advisor to the Amerindian People's Association of Guyana (APA) and the author of several works assessing the socio-economic impact of mining projects, was invited to Guyana last December by the APA, who expressed concern about earlier reported pollution incidents at Omai.

"He was unable to get permission to visit the site. He told American Reporter News Bureau yesterday that "the mine was hastily built, ill planned and an example of greed masquerading as the hope of a poor country." The mine is a subsidiary of Invesco, Inc., a Denver, Colorado-based mutual fund giant. Among that company's outside directors is the CEO of Atlanta 1996 Olympic Games. The Canadian engineering company Knight Piesold hired by Omai Gold Mine to build the tailings dam say they were very embarrassed by being associated with the failure.

"The company has built hundreds of tailings dams and this is the first time something has happened like this," a company spokesman said. However, the firm believes that Omai further developed the tailings dam after Knight Piesold left the project, raising the walls from the 25 metres state Knight Piesold had designed to a height of 45 metres.

"The initial cyanide spill in May was reported as being due to a power failure which had prevented sluice gates from being closed. This suggests that the gates were already open at the time of the failure, perhaps for a deliberate controlled discharge of effluent.

"Such a deliberate release is entirely plausible. Omai Mines had intended from the very first to release overflows from the polluted tailings dam into the river in its original Environmental Impact Statement to the previous Guyanese government. The current government apparently inherited a tacit agreement to this controlled release, along with a five percent equity share in the mine.

"A major force in bringing the mine to reality was Canadian mining investor Robert Friedland, who at the time was reeling from a gold mine's tailings dam disaster at Summitville, Indiana, the most expensive such failure in the U.S. in recent times.

"The Environmental Protection Agency (EPA) has estimated that the final cost of clearing up the cyanide and heavy metal pollution at the Summitville mine will be about $120 million. Friedland is still wanted for questioning by the EPA.

"After the Summitville disaster, Friedland invested in Omai Gold Mines Ltd. through Golden Star Resources, the subsidiary of Canadian-based Cambior, Inc. and Invesco, which operates a $9 billion mutual fund specialized in high-risk securities from "emerging nations." Golden Star Resources is now a 35 participant in the mine. Friedland is now believed to have sold his holding in the Omai mine and to have moved on to establishing one of the world's largest new gold mines on Lihir Island in Papua New Guinea." (2)

"The Québec Superior Court dismissed the case in August 1998, on the grounds that the courts in Guyana were in a better position to hear the case. A lawsuit against Cambior was filed in Guyana, but it was dismissed by the High Court of the Supreme Court of Judicature of Guyana in 2002. A new suit was filed against Cambior in 2003 in Guyana again seeking damages for the effects of the 1995 spill. In October 2006, the High Court of the Supreme Court of Judicature of Guyana ordered the dismissal of the 2003 action and ordered the plaintiffs to pay the defendants' legal costs. (3)

"In August 1998, within the three-year limitation period, a similar Representative Action was filed in Guyana. OMAI has now been served with the Action claiming to represent some 23,000 individuals in Guyana and seeking US $100 million as compensation for damages. The Action remains open to challenge in numerous respects, and Cambior and OMAI have instructed their attorneys to contest it vigorously" (1)

Sources:

(a) http://www.thefreelibrary.com/Cambior+Inc.+Announcement.-a055509330
(b) http://www.monitor.net/monitor/9-18-95/eyewitness.html
(c) http://ejatlas.org/conflict/omai-gold-mine-tailings-dam-guyana
(d) http://www.multinationalmonitor.org/hyper/issues/1995/11/mm1195_04.html
(e) https://ujdigispace.uj.ac.za/handle/10210/7295

(5) **MARINDUQUE**

Natural Damage Rehabilitation:

Tailings rehabilitation: Dredging of Boac River (Bennagen, 1998, Table 13)

US1996 $114 million = US2014 $172 million (www.usinflationcalculator.com)

Socioeconomic Loss:

Present Value of Current and Future Foregone Income for 10 years = P1996 $180 million
(At a discount rate of 15%, see Bennagen, 1998, Table 7)

P1996 $180 million = US1996 $8.77 million (www.x-rates.com/historical)

US1996 $8.77 million = US2014 $ 13.23 million (www.usinflationcalculator.com)

TOTAL: US1996 $122.8 million = US2014 $185 million

Operator Placer Dome Subsidiary Marcopper Mining

"This may be the amount used in some or all of the claims filed against Marcopper by fisher folk & other private citizens (which was not sustained). These damages are clearly not about clean up and only partly about loss of the rivers other functions in the ecosystem. We have therefore treated them as an amount separate from the $100 million government suit against Placer.

Background & Summary Notes

"The banks of the Boac River still hold tall mounds of tailings that were left to continuously pump acid and heavy metals into the river after another catastrophic dam failure filled that river with mine waste in 1996. These contaminated rivers no longer support the livelihood and economic activities of nearby villages, as they once did. Placer Dome, which had managed two copper mines in Marinduque, fled the Philippines in 2001, leaving the mess behind.

In spite of a long legal struggle with competent American lawyers, on Sept. 17 Marinduque provincial administrator Eleuterio Raza told the Inquirer that Barrick had offered the province around $20 million, take it or leave it." (4)

The cleanup of mine waste in contaminated sites around the world indicates that rehabilitation on a scale that is required in Marinduque can easily run into hundreds of millions of dollars. (4)

"Numerous independent scientific studies of the ravages of mining on Marinduque, including by the United States Geological Survey, confirm the ongoing toxic impacts of uncontained mine waste and unrehabilitated rivers and coastal areas. Furthermore, numerous dams and structures have not been maintained since the mine ceased operations in 1996. Placer Dome's own consultants, Canada's Klohn Crippen, warned in a 2001 report, leaked just before Placer Dome fled the Philippines, of "danger to life and property" related to inadequate mine structures holding back waste." (4)

The incident resulted in the release of 1.6 million cubic meters of tailings along a 27km span of the river system and coastal areas near the river mouth of the island province. The impact on the river eco system was extensive. The devastating effects of the pollution on the river and costal ecosystems was of such a magnitude that a UN Assessment Mission declared the accident an environmental disaster. Boac River was left virtually dead. The onrush of tailings downstream displaced the river water, which in turn flooded low lying areas destroying crop farms and vegetable gardens along the banks and clogging the irrigation waterways to rice fields."

Oxfam, an international development and humanitarian aid agency with projects in the Philippines was approached by Marinduque community members for help. Oxfam Australia's Mining Ombudsman took their case and released a report. The report calls on Placer Dome to complete an environmental clean-up, adequately compensate affected communities, and take steps to prevent future disasters. The report updates similar findings made by the United States Geological Survey in July 2004. As of 2005 Placer Dome (which ran the mine at the time of the disaster) was the sixth largest gold mining company in the world and was listed on the Toronto Stock Exchange, but was acquired by Barrick Gold in 2006. At the time of the incident Marinduque was identified as among the 44 poorest of the 80 provinces in the Philippines

On October 4, 2005, the provincial government of Marinduque sued Marcopper's parent company, Placer Dome, for $100 million in damages.

Sources:

(a) http://www.slideshare.net/no2mininginpalawan/major-tailings-dam-disasters-in-the-philippines-alyansa-tigil-mina-atm-april-2011-7819384Philippines
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(e) Bennagen, 1998. Estimation of Environmental Damages from Mining Pollution: The Marinduque Island Mining Accident, Ma. Eugenia Bennagen, Economy and Environment Program for Southeast ASIA, November, 1998

(6) **MERRIESPRUIT**

R1995 R100 million = US1995 $29 million = US2014 $46 million

Operator Harmony Gold

Despite the well documented and oft cited magnitude of loss, an entire village and many lives, and despite a judicial inquest there was no authoritative estimate of the economic value of that damage. The R100 cited above gave no source and no details and clearly is a significant under accounting of damage from a run out of this volume and length.

"Little attention was given to the environment. The identified need in this study was therefore to investigate the consequences of the disaster on the environment, a need which derives from the uniqueness of this particular disaster and its consequences. The Department of Minerals and Energy require the submission of an Environmental Management Program Report (EMPR) on all prospecting and mining operations. It is clear that, in the compilation of such an EMPR, Harmony Gold Mine neglected to establish a Management Plan to regulate the physical impact of the disaster on the environment, mainly because no attention was given to disasters in the Aide-Memoir."

Damages were estimated at R100 million (1)

The year before the disaster, a leak was reported, so all deposition was cancelled in to that particular compartment. Extra water was filtered into another compartment. Before the dam failed, the conditions were considered unsafe and unfit. The freeboard (which contained the extra water) did not have the ability to hold half a metre of extra water. But still, nothing was done. (1)

Management failures at Merriespruit:

- The inquest judge laid the blame for the disaster at the doors of the contractor, the mine, and certain of the contractor's and mine's employees. Failings of these parties that were illuminated at the inquest were as follows:
- There was no review process for the operation of the storage that involved an independent reviewer. The mine's and contractor's familiarity with the chronic problems of the storage resulted in complacency about their seriousness.
- The only involvement of a trained geotechnical engineer in the problems of the storage was that of an employee of the contractor, who became involved occasionally, only by request, and whose roles and responsibilities were ill defined.
- There were regular meetings between the mine and the contractor. However, decisions were poorly recorded, which led to confusion about responsibilities and agreed actions.
- The contractor's office at the mine did not keep the head office adequately informed of happenings at the storage. The head office was ignorant of problems and potential problems at the site and could thus not take corrective action.
- The contractor's local office was aware that water was being stored in the storage by the mine, but it took no action and did not inform either head office or seek the advice of its geotechnical engineer.
- Although the contractor had operated the storage since its inception, he had never been requested to upgrade the facilities of the storage and so bring it in line with acceptable practice, as spelled out in the industry guideline. (Chamber of Mines of South Africa 1979, 1983). Thus, the storage continued to be operated without a return-water pond. This necessitated storing water in the storage.
- Remedial measures taken to restore the stability of the northern wall were ad hoc and not the result of an adequate geotechnical investigation and design. (3)

Source:

(a) https://ujdigispace.uj.ac.za/handle/10210/7295
(b) http://floodlist.com/africa/merriespruit-tailings-dam
(c) https://books.google.com/books?id=OdFp3wKyxJoC&pg=PA453&dq=merriespruit+slimes+dam+1994&source=gbs_toc_r&cad=4#v=onepage&q=merriespruit%20slimes%20dam%201994&f=false

(7) **TENNESSEE FOSSIL PLANT**

US2008 $1,200 million = US2014 $1.3 billion

Owner Operator Tennessee Valley Authority

On December 22, 2008, a retention pond wall collapsed at Tennessee Valley Authority's (TVA) Kingston plant in Harriman, Tennessee, releasing a combination of water and fly ash that flooded 12 homes, spilled into nearby Watts Bar Lake, contaminated the Emory River, and caused a train wreck. Officials said 4 to 6 feet of material escaped from the pond to cover an estimated 400 acres of adjacent land. A train bringing coal to the plant became stuck when it was unable to stop before reaching the flooded tracks.

Originally TVA estimated that 1.7 million cubic yards of waste had burst through the storage facility. Company officials said the pond had contained a total of about 2.6 million cubic yards of sludge. However, the company revised its estimates on December 26, when it released an aerial survey showing that 5.4 million cubic yards (1.09 billion gallons) of fly ash was released from the storage facility.

The TVA spill was 100 times larger than the Exxon Valdez spill in Alaska, which released 10.9 million gallons of crude oil. Cleanup was expected to take weeks and cost tens of millions of dollars.

According to reports filed with the EPA by the Tennessee Valley Authority, the 2008 TVA Kingston Fossil Plant coal ash spill resulted in a discharge of 140,000 pounds of arsenic into the Emory River -- more than twice the reported amount of arsenic discharged into U.S. waterways from all U.S. coal plants in 2007. (1)

In April 2009, TVA Chairman Bill Sansom said the company is facing "upward pressure" on its rates, stemming from several challenges, including the Kingston coal ash spill. TVA has already spent $68 million on cleanup, and it estimates the final cost could surpass $800 million, not including fines and lawsuits. The Associated Press reported on April 11 that TVA had already spent over $20 million purchasing 71 properties tainted by the coal-ash spill and is negotiating to buy more.

Although falling fuel prices have enabled TVA to cut much of a 20 percent rate increase that took effect in October 2008, the company is considering another increase in October 2009 to mitigate these expenses. TVA will set its fiscal 2010 budget and rate changes in August.

In September 2011, it was reported that TVA estimated the total cost of the cleanup will be $1.2 billion. The utility is self-funding, so ratepayers in the seven-state region are paying the tab with higher electric bills. (1)

On August 23, 2012, U.S. District Judge Thomas Varlan ruled that “TVA is liable for the ultimate failure of North Dike which flowed, in part, from TVA’s negligent nondiscretionary conduct.” The litigation involves more than 60 cases and more than 800 plaintiffs, and will allow their claims of negligence, trespass, and private nuisance to move to Phase II proceedings, meaning each plaintiff must prove the elements of his or her respective negligence, trespass, and/or private nuisance claims by a preponderance of the evidence.

In a Sep. 27, 2010 report, TVA's inspector general Richard Moore said poor coal ash control practices and the Tennessee Valley Authority management culture led to the huge December 2008 spill. The report on the inspector general's website describes the giant spill of coal sludge laden with selenium, mercury, and arsenic as "one of the largest environmental disasters in U.S. history." TVA said the description of the event as one of the largest disasters is "not supportable." Moore refused to change. (1)

(ATLANTA – May 18, 2010) The U.S. Environmental Protection Agency (EPA) Region 4 today has approved the Tennessee Valley Authority’s (TVA) selected cleanup plan for the next phase of coal ash removal at the TVA Kingston site in Roane County, Tenn. The cleanup plan, one of three alternatives proposed to the public earlier this year, requires TVA to permanently store on site all of the ash being removed from the Swan Pond Embayment, which includes land and bodies of water adjacent to the TVA coal ash disposal area. The embayment area will then be restored to conditions that protect human health and the environment. (2)

Sources:

(a) http://www.sourcewatch.org/index.php/TVA_Kingston_Fossil_Plant_coal_ash_spill
(b) http://yosemite.epa.gov/opa/admpress.nsf/2ac652c59703a4738525735900400c2c/106c22e4bc722561852577270062c9de!OpenDocument
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environments

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Article

In the Dark Shadow of the Supercycle Tailings Failure Risk & Public Liability Reach All Time Highs

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Abstract: This is the third in a series of independent research papers attempting to improve the quality of descriptive data and analysis of tailings facility failures globally focusing on the relative occurrence, severity and root causes of these failures. This paper updates previously published failures data through 2010 with both additional data pre-2010 and additional data 2010–2015. All three papers have explored the connection between high public consequence failure trends and mining economics trends especially grade, costs to produce and price. This work, the third paper, looks more deeply at that connection through several autopsies of the dysfunctional economics of the period 2000–2010 in which the greatest and longest price increase in recorded history co-occurred across all commodities, a phenomenon sometimes called a supercycle. That high severity failures reached all-time highs in the same decade as prices rose to highs, unprecedented since 1916, challenges many fundamental beliefs and assumptions that have governed modern mining operations, investment decisions, and regulation. It is from waste management in mining, a non-revenue producing cost incurring part of every operation, that virtually all severe environmental and community damages arise. These damages are now more frequently at a scale and of a nature that is non-remediable and beyond any possibility of clean up or reclamation. The authors have jointly undertaken this work in the public interest without funding from the mining industry, regulators, non-governmental organizations, or from any other source.

Keywords: tailings storage facility failures; supercycle; mining metric; tailings storage failure predictions

1. Introduction

Deficiencies in the storage and management of tailings, the post processing wastes of metals, hydrocarbons and fertilizer, are the largest source of high public consequence failures globally. Although each tailings storage facility (TSF) is described and represented to regulators as capable of meeting all applicable environmental and other regulations, and being fit for its intended use and purpose, law and regulation in the permitting and oversight process provides very limited regulatory scrutiny. Policy frameworks offer only broad standards and extremely limited life of facility oversight. High severity failures, when they occur, have tended to be viewed and presented by industry as unavoidable and unforeseeable. The assertion that local damages are more than offset by the greater good of providing the world's needs for metals, hydrocarbons, and fertilizers is unproven and unprovable.

Though preceded by 40 catastrophic failure events globally, two highly visible catastrophic failures, Mt Polley in Canada (2014) and the Fundao in Brazil (2015), have brought about the first global revisiting of this antiquated implicit assumption that mining impacts are unavoidable and offset by greater public need and benefit. Both industry and governments are now recognizing that loss prevention is both possible and imperative. The dramatic investor impact of the Brazil failure on two of the world's largest miners, BHP Billiton and Vale, has raised awareness in financial circles that the consequence of mine failure at this scale is not just on local communities and environments. Miners are aware that even with the protection of limitations of legal liability via subsidiaries, large-scale failures can have companywide ramifications and affect all operations.

That emerging conversation between industry and communities on the "path to zero failures", as it is called, has tended to focus on those physical attributes of tailings storage facilities that insure structural soundness during operations, and after closure into perpetuity. However, even before these two major failures, there was a growing awareness that the root causes of failures lay in other circumstances and conditions that shape the decisions made by miners on each facility, which are at variance with design requirements and with Best Practice, Best Science and Best Knowledge. The World Bank first made note that the key issue facing the industry and communities was the growing spread between ore production volumes and volumes of metal output from mining as available grades or ores fell globally [1]. That spread represents both a greater waste volume per unit of metal produced and often, as at the Fundao, the largest failure in history, results in a significantly greater rate of tailings deposition and more frequent and larger dam raises, undermining critical safety elements on which the original design depends. These deviations from design were identified by both expert cause of failure panels, Fundao & Mt Polly, as the principal physical cause of failure.

In 2001, long before these two notorious failures reached even small-town newspapers all over the world, the International Commission on Large Dams (ICOLD) announced their conclusion that the frequency and severity of tailings failures from metals, hydrocarbons and fertilizers was increasing globally. To keep that trend in the spotlight, they created a global failures compilation. The database for this work is developed partially from, and expands upon, the 2001 ICOLD database. In releasing their 2001 database, ICOLD announced their finding that the majority of these failures were avoidable and a matter of control and diligence by mine owners and operators. In their landmark 2001 report [2], they stated:

> *"...the technical knowledge exists to allow tailings dams to be built and operated at low risk, but that accidents occur frequently because of lapses in the consistent application of expertise over the full life of a facility and because of lack of attention to detail."*
>
> and;
>
> *"By highlighting the continuing frequency with which they are occurring and the severe consequences of many of the cases, this Bulletin provides prima facie evidence that commensurate attention is not yet being paid by all concerned to safe tailings management." (emphasis in original)*
>
> and;
>
> *"...the mining industry operates with a continual imperative to cut costs due to the relentless reduction in real prices for minerals which has been experienced over the long term, plus the low margins and low return on capital which are the norm. The result has been a shedding of manpower to the point where companies may no longer have sufficient expertise in the range of engineering and operational skills which apply to the management of tailings."*

It is to a further exploration of these prescient observations by ICOLD and the World Bank that this work, and the two prior works of this research partnership [3,4], have been addressed. Prior work of this partnership had begun to piece together considerable evidence that financial risk and environmental risk, as well as other public liabilities, are very closely related. This is suggested as a root cause of failure, both in the observations and findings of the World Bank seminal study, and in the very clear statement of findings by ICOLD. In the 2015 work by these authors, it was reported that the data confirmed a greater need to more carefully and independently track initial and life of mine economic viability as a key strategy for loss prevention.

Deeper inquiries and empirical evidence of what the World Bank and ICOLD pointed to as already established as a trend before 2000 has been made possible by extensive improved data on failures prior to and since 2000 and the development of an empirically based typology of failure severity and incident type [5]. While claiming no statistical proof of causality, appropriate multivariate analytic methods have been applied to explore root causes, and to identify areas in which changes in public law and policy might be more effective in preventing public loss and liability. At the broadest level, the tailings research work by these authors suggests that all high-consequence/high-severity failures are failed public-private partnerships attributable to gaps in policy that fail to adequately identify, defend, and protect the public interest. The authors see regulatory reform more focused on loss prevention and pre-application risk assessment as a more fruitful, and possibly more effective, approach to better outcomes than the presently prevalent use of fines and penalties as deterrent and punishment.

With a view to elevating conversation and deepening understanding of how to improve and correct present trends of public loss from TSF failures, the three works of Bowker-Chambers 2015 [3], Bowker-Chambers 2016 [4], and this paper, are pure research in the sense of not starting with a hypothesis to be proved, but coaxing as much reliable information from what reliable data can be assembled. The authors have set about to make a more complete description of what the World Bank and ICOLD pointed to as the previously un-explored relationship between the economics of mining and the history of tailings dam failures.

This paper presents an overlay of new analysis by industry experts on the 2000–2010 decade of the previously studied period, 1946–2009. The period 2000–2010 has been described by the Hamburg Institute of International Economics [6], as the longest and strongest supercycle in recorded history. A supercycle is a period in which all commodities co-entrain in a sustained multi year period of price increases.

It is customarily assumed that as prices rise, profits and performance also rise with a concurrent effect of fewer high public severity failures. This paper challenges that notion through the authoritative findings of top mine analysts who found that performance during the supercycle was actually very lax as compared to the tight control in leaner times resulting in an unprecedented level of investor losses and write offs as prices across all commodities pushed steadily upward to post-1916 highs in 2011. Copper, the bellwether for base metals, reached a post-1916 high of $9411 ($2015) as compared to the prior 50-year average price of $5133 ($2015) [7]. Looking at failures, the incidence of highest severity TSF failures also reached a post-1916 high of 1.0 high-severity failures per year, as compared to the previous 50 mostly lean years of 0.56 high-severity failures per year.

These indisputable facts challenge the notion that failures are mostly shaped by the squeeze of falling prices.

This new data analysis by top mining economists, and analysts and the revised more comprehensive failures data developed by the authors, shows that prices do not bring better performance and fewer failures as many regulators continue to believe.

The consensus assessment by leading mine analysts Deloitte [8], McKinsey [9], Ernst & Young [10], and Price Waterhouse [11] is that the unexpected price surge created by Chinas high demands for all commodities lead miners to abandon business fundamentals and engage in a frenzied push for high production at any cost. Several of these works specifically address the pushing of economically marginal mines to achieve production goals as a contributing cause of massive investor losses. The ICOLD 2001 attribution of depressed prices and falling grades as a root cause of failures might reasonably lead to an assumption that as prices rose they would fund the restoration of the technical and engineering capacity that was shed and lost in the long price fall, and result in fewer high public consequence failures. In essence, what these top mine analysts concur is that instead of rebuilding engineering and technical capacity and catching up on deferred infrastructure maintenance and needed improvements, many miners counted on price alone to make up for these accrued dry times deficiencies. They expected to achieve profits within the portfolios and corporate capacity that existed at the very bottom of the long down ward leg of the preceding supercycle. In fact, the long and never imagined surge in prices over the supercycle actually brought the worst performance in recorded history not just as measured by the severity and number of high public consequence tailings failures, but also in investor losses, massive write offs and an impairing level of miner debt.

Now, in the down leg of that 2000–2010 supercycle, with grades and prices well below 2011 peaks, there is no within industry appetite to take on the loss prevention reforms summing several decades of mine by mine failure analysis that were offered by the Mt Polley Expert Panel. The industry's first priority is on economic recovery and debt reduction, which has been demanded by investors. From a public interest point of view, the first priority has been expressed as complete and immediate commitment to the entire framework of reform offered by the Mt Polley Expert Panel.

Industry and mine regulators have avoided the major thrust of the Mt Polley framework for reform. Neither the International Council on Mining and Metals, the Mining Association of Canada, or any government known to the authors, has undertaken, or committed to, the key reforms necessary to achieve TSF failure loss prevention. All mines since approved the government of British Columbia, who commissioned Mt Polley Report, violated the main recommendations [12].

The possibility that this is more than a conflict in priorities as between public interest demands and the industry (including its regulators), is suggested in a new work by a research team of leading experts in the economics of extractive industries [13]. Their work was about examining how business decisions are actually made by miners but the data they added provides a background to the failures history, which suggests that the conflict has origins that are more fundamental. To lower debt as investors have demanded and streamline operations, miners have been engaged for several years in a shedding of the marginal assets they pushed into production during the supercycle. The Aguirregabiria & Luengo study [13] suggests that the total portfolio of mines that are not presently viable and or likely to become viable without significant new discoveries may be as high as 30% to 50% globally. These will become further write offs if they cannot be marketed to new owners as possible future earners. It is reasonable to assume that adoption of the Mt Polley reforms for all operating mines would make many of the mines in this 30% to 50% of the global portfolio "stranded assets". It would be difficult at the very least to add value through a new or expanded permit or though transfer of existing permits. The public interest sector does not accept that the reforms should only apply to new facilities and that all existing facilities should be managed to closure in accordance with best practices. Thus, the reforms demanded by the public interest sector may conflict fundamentally with the recovery strategy of the industry. Adoption of the Mt Polley framework as policy for all tailings facilities, as the public interest sector demands, could also necessitate closure and its associated capital and other expenses, something that miners and regulators have resisted. This would be especially problematic for the 30% of technically active mines that were not able to produce at all in the super cycle.

The Aguirregabiria & Luengo study also suggests that the relationship between price and failures during periods of high price rises invites more participation in metals production by marginal and poorly vetted mines, which is probably why we have not previously noted correlations between price and other variables.

The authors of this study view this massive spinoff of marginal mines from deeper pockets to more speculative and often less experienced miners as posing a fundamental and difficult to overcome challenge to the public interest goal of reforms necessary to zero failures.

A major purpose of this paper is to describe this crisis of conflicting public interest and miner priorities. The authors believe strongly that an all-stakeholders multi-disciplinary approach to resolving this dilemma can resolve it to the satisfaction of all. The authors do not believe that we need to accept the present high level of catastrophic failure as the new elevated cost of meeting the words needs for metals, hydrocarbons and fertilizers. The partnership in research failure studies that the authors have formed is premised on the belief that at the global level, the world's needs for metals, hydrocarbons and fertilizers can be met, responsibly in the short term, and sustainably in the long term.

2. Methods

This paper has three major analytic components:

(1) A reexamination of the findings and conclusions of two earlier papers [3,4] reporting on failures for the period 1946–2009, in light of new failures data which had developed on pre-2009 failures as of July 2016. A primary objective of this component is to report notable changes in findings especially with respect to failure trends and relationships to economics data.

(2) The reporting of new insights on the dynamics of price over the period 2000–2010, which has been described as a supercycle, a period of price co entrainment of all commodities. In the 2000–2010 supercycle, commodities prices reached all-time highs. Because price itself had, and still has, very low correlations with all other data elements, earlier work by the authors had not been able to directly explore the role of price in failures trends and severity. Unfortunately, that has not changed. However, a number of supercycle autopsies written by reputable mining analysts, by cross reference and overlay reveal more about the dynamics of price in relation to failures, but more importantly have considerable bearing on what could only be inferred about root causes of failure from previously available data.

(3) A reexamination of trends and predictions with both failures and economics data through 31 December 2015.

The failures data for all three analytic components of this paper is Chambers Bowker TSF Failures Database as it existed on 15 August 2016. That version of the failures database, in downloadable excel form, is the technical documentation for all failures-reported data in this current work. All technical documentation, raw data, and technical analysis has a tab within the database bearing the same title as the chart or table in the paper.

For all descriptive and analytic work on trends in failure severity, and in level of severity, the same format and data elements are used for all charts and tables as presented in the two earlier works. All notable confirmations and new insights are noted, but for the sake of brevity, old data and new data are not presented side by side. This approach facilitates comparisons and evaluation by other researchers, while keeping the focus on present conditions trends and new insights. The publicly available database does include these side-by-side comparisons with notes and commentary.

All of the failures data is from our own tailings database, which is an enhanced, more complete, version of the global World Information Service on Energy (WISE) Uranium Project database. Enough additional authoritatively documented data on release volume and runout has been compiled to present it as an independent measure of increasing severity.

Best fit is presented on trend lines with R2s for all chart data, not to establish or assert statistical significance, or in the case of our regressions and multivariate analysis, to demonstrate causality, but only to describe and characterize relationships and trends.

Bowker-Chambers 2015 [3] included an extensive documentation on the predictive methods and on the use of Canonical Correlation Analysis (CCA) to explore the relationship between high severity failures and global mining economics. That previous documentation is relied on as the technical documentation for this paper, both for the CCA and our revised failure predictions. The new CCA runs, with both CCA comparisons to the prior runs, are included with the publicly available database on which this paper is based. In the paper itself, only changes in the key outputs of the CCA are presented and analyzed, in comparison with the 2015 CCA.

Much of Hoteling's work was addressed to the economics of extraction of non-renewable resources. CCA is his creation, and intended to explore the dimensionality of relationship between two data sets with no established prior interdependence. In the case of the author's three works, the data sets are the economics data and the failures data.

Copper ore production is used as the surrogate for all failures (not just all metals, but for all reported failures, including hydrocarbons and fertilizers). Time will tell whether our success in accurately predicting failure occurrence rates relies on the fact that all commodities were co-entrained in the supercycle, or whether copper will remain a reliable way of expressing failure rates and predicting all failures. It has proven itself reliable, so far. The analysis suggests that copper stands in well pre- and post- 2000–2010 supercycle, for purposes of predicting future failures for all commodities in the failures database, all other metals, hydrocarbons and fertilizers.

For one major 2014 failure, Mt Polley, the largest failure in Canada's history, a pre-failure history of the economics of the mine was developed using the annual reports and other publicly available data presented by the owner.

The predictive methods developed in 2015 [3] are based on the loss-development methodology for property and casualty ratemaking generally employed by the Insurance Services Office and by most in-house rate-making by major insurers. This paper relies on the extensive prior documentation in our other papers as adequate and relevant documentation for this work as well. This method accurately predicted total Very Serious Failures for the period 2006–2015 based on the 1946–2009 data alone. We report the revised prediction results using the same previously documented method. The raw data runs, and annotation, are included in the publicly available database for this paper.

The Chambers Bowker failures database now includes mine specific data on throughput to date of failure, resource grade by metal, and estimated Cu eq. (Cu eq. is the equivalent of Copper grade taking into account saleable other metals). This data is not yet available for all failures in the database, or for all high severity failures, but we have reported key statistics from what we have.

For this work, further exploring economics as a root cause of failure, the original mining economics database-by-decade was expanded to a publicly available annualized global database of the main economic descriptors; grade, copper production, price, ore production, and ore productions costs. The database [14] includes complete technical documentation on sources and compilation methods, as well as tabs with raw data for all charts and tables in this paper, which were produced from that database.

While the two major original data compilations supporting this work may be the most comprehensive set of data presently publicly available globally geared to TSF failure studies, both are far from complete and still missing data on many variables for major failures. Still, we believe the results have spoken usefully and reliably through our chosen methods and compilations.

3. Results & Discussion

3.1. New Insight on the Economics of the Previously Studied Period through 2010

The impetus for this paper and its title was the additional analysis on the economics of mining over the previously examined period (1946–2009) in which the trend to catastrophic failure emerged. This new information came in the form of many authoritative independent analyses of the dynamics and fallout of the supercycle. They observed that the sustained and significant rise in prices brought not stability, higher profits and success, but also massive write-offs and huge investor losses [8–11], in addition to what had previously been documented from the public interest point of view as the worst failure performance in recorded history [3]. An important independent work by Aguirregabiria and Luengo [13] added further insight through its examination of 333 mines over the period of emergence of the high public consequence failure trend.

3.2. Supercycle Dysfunctional Economics

The dysfunctional, reactive economics of the supercycle are expertly analyzed and well characterized by Deloitte in their 2014 market trend analysis. "*In their relentless pursuit of growth in response to pressure from investors and analysts, companies developed massive project pipelines. Some also developed marginal mines, hoping commodity prices would buoy poor project economics. In their headlong pursuit of volume, many mining companies abandoned their focus on business fundamentals. They compromised capital allocation decision making in the belief that strong commodity prices would compensate for weak business practices. Rather than maintaining a long-term view of the market, many acted opportunistically.*" [8]

Price Waterhouse Coopers, looking at the performance of the top 40 over the supercycle, note that much of the massive commitment of capital to expansion and production at any cost ended up as impairment write offs: " . . . *from 2010–2015, the top 40 have impaired the equivalent of a staggering 32% of the capex incurred*". They note that $36 billion, or 68% of the total impairments, were taken by Glencore, Freeport Vale and Anglo American and that "*2015 saw the first widescale mothballing of marginal projects*". The top 40 took a collective net loss of $27 billion and investors punished them for "squandering the benefits of boom" and for "poor capital management and investment decisions" [11].

It is in this dysfunctional "maximum production at any cost" dynamic of the supercycle that the dramatic upturn in the frequency and severity of failures occurred, and in which there is with very little doubt a higher global portfolio risk of accrued and unexamined public liability. As presented in Section 3, changes in waste to metals ratios for gold suggest the possibility of a more than 100% increase in the level of potential unexamined risk [15].

3.3. Additional Analysis on the Entire Period of Emergence of the Trend to High Severity Failures

A recent study of actual annual mine records of 330 mines comprising 85% of world copper production sheds some light on the economics that may apply for all metals, and may hold keys to a deeper understanding of the relevant economic red flags of possibly incubating failure conditions [10]. The study reports that on average only 52% of mines were active at any time in their study period, 1993–2010 (173/330) and that 32% produced no mined output at all during the supercycle (maximum active was 226). This suggests the possibility that from 30% to 52% of all "still open" copper mines globally may not be economically feasible and cannot be expected to generate revenue sufficient to cover production costs. In many instances, perhaps mines should never have been developed in the first place. Certainly, no one would dispute there are many mines which have never been profitable, and have frequently been in and out of production due to price sensitivity.

As Figure 1 shows, based on the Aguirregabiria & Luengo [13] report, in the run up of the supercycle the active participation among the 330 mines swelled from 144 (44%) to 226 (68%), viz. an average of 173 active at any one time. It is in this increased re-entry, and often expansion of economically fragile mines (see Price Waterhouse Coopers [11]), that the trend to ever-increasing severity and frequency of catastrophic TSF failures has manifested.

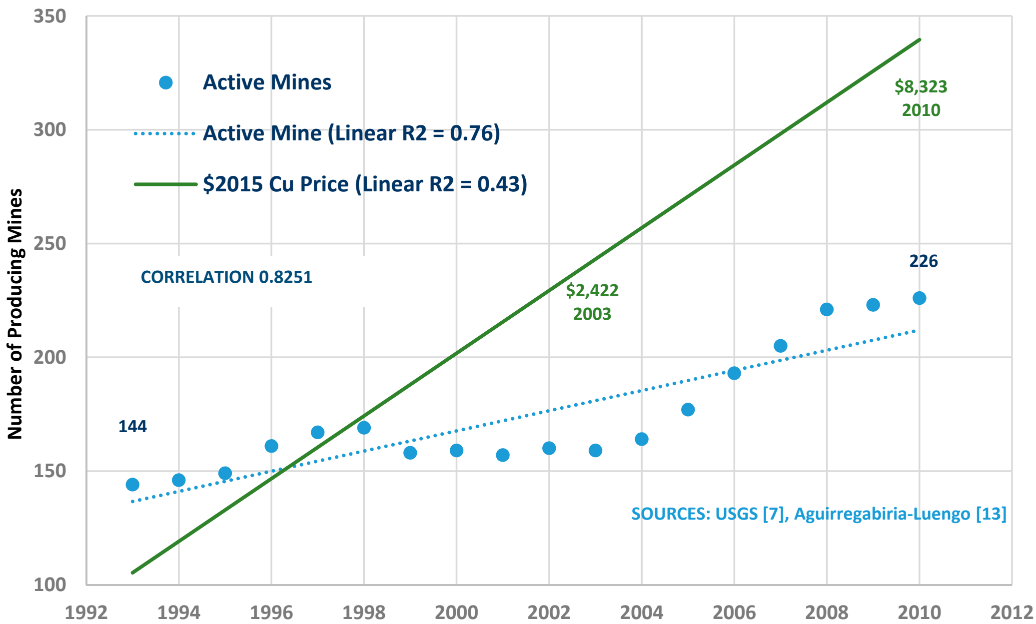

Figure 1. Number of producing mines & increasing copper price.

In response to investor demands for miners to reduce debt, there has been an aggressive campaign to clear these marginal mines from the portfolios of the top producers. Leading industry economists agree that this is a healthy restructuring at the company level. From the public interest point of view, however, this widespread cleansing is problematic because whatever risks have accrued in the waste facilities of these non-performing mines, and mines pushed beyond design capacity in the production fever of the supercycle, remain unexamined. Whatever problems exist have not been corrected. Based on the Aguirregabiria & Luengo study, it appears that without significant new discoveries, perhaps as many as 30% of all currently permitted mines may never produce revenue again, and have had a poor history of production. It is reasonable to assume based on what is known about the history of TSF management that most are upstream construction, have slurry depositions of unstudied stability, and by design or neglect have water covers, which are all markers of elevated risk.

Prior to transfer to new owners, regulators have avoided enforcement and ducked corrections at these marginal mines hoping for a return of prices that will allow problems to be addressed out of mine revenues. For the 30% of mines that were not able to produce at all during the supercycle, it seems unlikely there will be any new revenue soon, or perhaps ever, without major new discoveries or major new technology breakthroughs. Therefore, a healthy restructuring from the point of view of mine companies effectively represents a transfer of the TSF failure risk of these mines to the public, as there are no mechanisms in place to force corrections or closure outside of the application and permit process. Even after re-openings, regulators fear that enforcement actions may trigger bankruptcy, as occurred at the short-lived reopening of the Yellow Giant Mine in Canada.

Regulators who believe that rising prices will restore production and bring revenue to fund negotiated correction and closure of any serious TSF problems will have either to fund it themselves or accept the consequences of failure.

3.4. Updates to pre-2010 Failures Data and Revised Predictions 2010–2020

Between the release date of the 2015 paper, reporting analyzing failures 1946–2009, and preparation of the current paper, a great deal of new information developed on the pre- 2009 failures and significant incidents. This new information included both the details of failures already in the database, and the identification of previously unreported failures. It is normal in all loss development for there to be an estimable amount of what insurers call incurred but not reported, but in this case the identification of three additional high severity failures resulted in an unusually significant change from 7 to 10, a 42% rate of unreported high-severity failures. This has resulted in an upward revision of the predicted number of high-severity failures in 2020–2020 from 11 to 13.

Analysis on the impact of the revised data on earlier reported trends and descriptive statistics from 1946 to 2009 indicates that the chronic condition of incomplete reporting, even in the Chambers-Bowker Failures Database, has no effect on the bottom line findings and conclusions. What did emerge, and is reported in the next section, is a greater clarity on the second highest severity category, as well as some very interesting changes in the relationship between the two databases, failures vs mining economics.

The unreported very significant failure that did not appear in WISE, or in any other compilation, was in Brazil, and is well known throughout the mining industry. ICOLD's wise design for the data base, and the foundations it created on the initial 221 records, and the work WISE has done stands up to even a 40% under-reporting rate of high severity failures. The database still tells its story. The WISE database appears to be sourced mainly by direct reporting from the industry, and often encompasses under-reporting or missing runout and release data. The publicly available Chambers-Bowker database [5] is far more complete than the WISE database. It is sourced directly from the communities where the mine is located through media accounts, technical reports, and court records, and is supplemented through continuous multi-language scan available online, and by inviting authoritatively documented corrections and additions. What has been added to the WISE database from this process has made it possible to do deeper and broader analysis of failures and failure causes.

3.5. Failure Updates and Revised Analysis through 2015

There has previously not been sufficient data on the release volume or runout distance of failures to conduct any meaningful analysis on these variables. By ICOLD's design, all records of release events were to have this data, but as of the Rico study in 2007, they had to look to other sources to gather 28 records with both release and run out [16]. The new data added to Chambers-Bowker has nearly doubled that number, making it possible for the first time to make a preliminary report on severity, as measured by release and run out, across all failure categories. As graphically illustrated in Figure 2, the absolute number of major failures, and the severity of all failures as indicated by cumulative release and cumulative runout per decade, has steadily escalated reaching all new highs. The present decade (2006–2015) captures the steepest part of the price run up of the supercycle, and just the beginning of the steep and sudden downward leg. It is important to note that the escalation of severity, as measured in release volumes and run out distance for all recorded events, is nearly parallel with the slope of the trend lines of the two high-severity classifications. This indicates the possibility of common root causes, even for the lowest severity failure events. It also confirms that the magnitude of all significant events is increasing, and is affecting ever-larger areas by the increasing runout and release of the failure events.

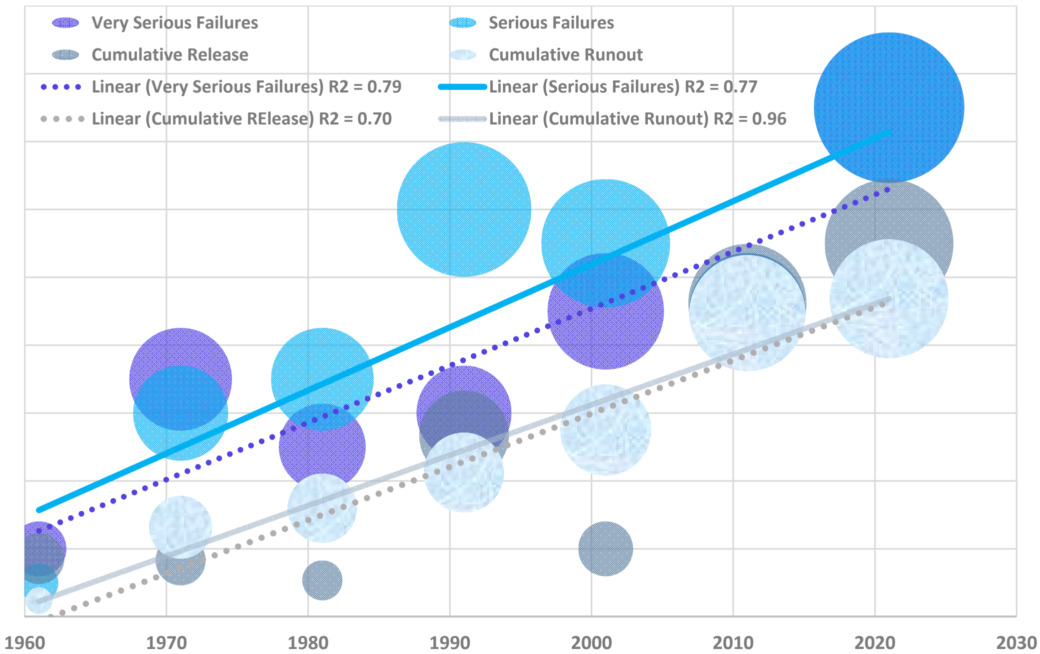

Figure 2. Increasing severity & frequency of tailings storage facility failures.

Estimating major failures by proven actuarial methods [4] and projecting cumulative runout and release by trend line, the overall severity profile for the coming decade, 2016–2025 (Table 1), will be 67% higher for both major failure categories and severity will reach all-time highs with more modest projected increases of 5% and 8% respectively.

Table 1. Anticipated increases in frequency & severity 2016–2025.

Time Period	Very Serious >1 Mm^3	Serious >100 Km^3	Cumulative Release Mm^3	Cumulative Run Out km
2006–2015 (actual)	9	9	895	92
2016–2025 (predicted)	15	15	937	110
Projected % change	+67%	+67%	+5%	+8%

Although not statistically significant by normal standards of minimum observation size, the fit to a linear trend line and the strong r-square values for both Serious and Very Serious failures and for the two severity elements shown in Figure 2 completes the compelling and persuasive forensic evidence of increasing frequency and severity of TSF failures.

The data set on all 290 events in the failures database is shown in Table 2 with predictions for 2010–2020 and for 2016–2025 on a per million tonnes of Cu ore production basis. The 2010–2020 projection has increased from 11 to 13 based on the additional five years of failures and substantially more complete information on pre-2010 failures. Predictions for 2016–2025 are 15 for both high severity categories, an annual rate 67% higher than the 2006–2015 decade.

Table 2. TSF Related Failures & Events by Severity 1906–2015.

Decade	Dam Failures "Significant Events"			"Other Events"		Total
	Very Serious	Serious	Other	Non-Fail	Non-Dam	
1916–1925	0	0	1	0	0	1
1926–1935	1	0	0	0	0	1
1936–1945	1	0	7	0	0	8
1946–1955	1	1	5	0	0	7
1956–1965	3	1	30	0	1	35
1966–1975	7	6	37	0	4	54
1976–1985	5	7	36	2	2	52
1986–1995	6	13	34	3	0	56
1996–2005	9	11	17	0	0	37
2006–2015	9	9	16	3	1	38
	=======	=======	=======	=======	=======	=======
Occurred	42	48	183	8	8	289
Pred. 2010–2020	13	13	n/av	n/av	n/av	n/av
Pred. 2016–2025	15	15	n/av	n/av	n/av	n/av

Source: Chambers-Bowker TSF Failures [5].

3.6. Root Causes of Failure beyond Proximate Cause

Virtually all Very Serious Failures in recorded history were preventable, either by better design or by better operational management. Although ICOLD was the first to authoritatively name it in 2001, it is widely recognized now that proximate cause (the precipitating final physical cause of a major failure) of failure is not a matter of force majeure, unforeseeable and uncontrollable events, black swans (high severity loss that results unforeseeably from the cumulative effect of a large number of small events or conditions), or ordinary human error, but a result of conscious decisions at odds with Best Practice, Best Knowledge and Best Available Technologies. Of course, the proximate cause of all TSF dam failures is geophysical and structural in nature, but the root cause is a failure to design, build and manage TSFs to known Best Practice, Best Knowledge, and Best Available Technology. Though few put it in these plain terms, the Mt Polley Expert Panel, convened by the Government of British Columbia to examine causes of the Mt Polley failure, and to make recommendations for applicable to all tailings facilities, was very clear.

In Brazil and British Columbia, professional practice and regulatory guidance allowed unrestrained reliance on the Observational Method, a term of art in mining that refers to a continuous, managed and integrated process of design, construction control, monitoring and review enabling appropriate, previously-defined modifications to be incorporated during, or after, construction.

The Mt Polley Report notes:

> *"The Observational Method ... relies on recognition of the potential failure modes, an acceptable design to deal with them, and practical contingency plans to execute in the event observations lead to conditions that require mitigation. The lack of recognition of the critical undrained failure mode that prevailed reduced the Observational Method to mere trial and error."* [17]

The Fundão dam had serious construction flaws in the base drain and filters, concrete decant galleries were structurally deficient, operational deviations allowed structurally weak slimes to be deposited in areas where they were prohibited by the operating plan, and the dam crest was moved and constructed over these slimes causing the dam failure [18].

At Mt Polley, the miner deviated from the construction design, and the review committee found the dam would not have failed if the original design had been followed, despite the undiscovered glacial lake beneath the dam [17].

All of the earthquake triggered failures in Chile in the 1960s were found to be associated with the prevalent use of upstream construction for TSFs in an area known to be prone to frequent, high severity earthquakes [19].

With the exception of recent updates to law and policy in New South Wales [20], Australia, which requires use of the Australian National Committee on Large Dams (ANCOLD). Guidelines on Tailings Dams Planning, Design, Construction, Operation and Closure [21]. We are not aware of any other legal framework for mining that enforces a primary Best Practice/Best Available Technologies performance standard life of mine. Regulatory agencies do not formally adopt existing guidelines like ANCOLD, leaving industry to depend largely on their own or consulting engineers without independent review to make key decisions affecting public risk and viability. As the Mt Polley Expert Panel noted, the standard applied in this prevailing framework often puts economic exigencies and production schedules ahead of the public interest.

It is widely acknowledged even by the industry and major industry trade groups that Best Knowledge and Best Practice and Best Available Technology will not be universally applied without a legal mandate. For example, the standards adopted by the Mining Association of Canada (MAC) and [22] and the International Council on Mining and Metals (ICMM) [23] leave the final determination to the individual mine site or company. The British Columbia Ministry of Energy and Mines (BC MEM) response to the Mt Polley Expert Panel recommendations avoided several of the main recommendations of the Mt Polley Expert Panel to the point where BC MEM requirements will not adequately protect tailings dams from future failures [12].

The focus only on proximate cause in the autopsy of catastrophic events on the one hand, and the determined avoidance of Best Available Technology, Best Knowledge and Best Practice in law and policy on the other, sets up a system wherein it's easy to look to short cuts on all aspects of waste management practice without raising any concerns on the part of regulators or investors. To B.C. Ministry of Energy and Mines's credit, they did flag the exact location of failure two years before and did press for a full buttress, which was resisted and contested [17].

More importantly, the focus on proximate cause fails to address or understand the more fundamental root causes that result in these deviations where law does not require and enforce adherence to the application of best practices in all phases of TSF design, construction, operation, and closure, or to require expert independent review of key decisions affecting public risk and economic viability.

3.7. The Directly Measureable Relationship between Failure Trends & Global Mine Economics

The global economic history of metallic mining is best and most frequently described with four key variables: (1) volume of metals produced from mines, (2) realized price for that volume, (3) costs to produce, and (4) grade of ore to the mill. Over the past 100 years, the key dynamic of metallic metal mining globally for all metals has been declining grades and declining prices punctuated by a few short-term supercycles. As grades fell across all metals for discoveries, reserves and head grades, economic feasibility and the possibility of profit has turned mainly on the economics of ore production made possible through open pit mining. The cost to move a tonne of ore from the ground to the mill is completely independent of grade and of the ultimate price that will result.

This brings two additional key variables into play as the background economics that result in high failure frequency and severity: (1) ore production volume, and (2) the mining cost per tonne of ore.

Mine economist Richard Schodde correctly mapped the major historic role the unit cost of ore production has played in holding the line against falling grades, and against the long-term decline in prices [24]. He calculated that while overall mine costs, from 1900–2010, had declined by 50% in real dollars, that when distributed over ore volume, the per-tonne of ore production cost had declined 87%. This is what made the mining metric workable and profitable for some but not all. Schodde argued that the decline in ore production costs would continue to grow the resource even as grades continued to fall (discovery, reserves, and as milled). What the World Bank detected was the dramatically widening gap between ore production volumes and mined metals output [20].

This gap could also be described as declining yields on the economics side and exponential growth in wastes on the environmental side. In only eight years, from 2005 to 2013, the decline in yields for gold was 29%, from 1.68 g/t in 2005 to 1.20 g/t in 2013. On a waste to metals basis, that translates to a 117% increase from 52 tonnes/oz. to 113 tonnes/oz. [15]. It is to this gap of ever-declining yields, and its relationship to the emerging trends of catastrophic failures that prior research [3,4] and this paper are addressed.

The previously established correlations between failure severity and these five key mining economics parameters (Cu Ore, Cu Grade, Cu Metal, Cu Cost, Cu Price) is reaffirmed in failures and mine economics data as of December 31, 2015, as shown in Table 3.

Table 3. Changes in correlations 1940–2009.

As Known July 2015 v As Known July 2016					
Date/Severity	**Very Serious**	**Serious**	**Cu Ore**	**Cu Grade**	**Cu Cost**
Very Serious July 2015	1	0.880	0.860	−0.794	−0.788
Very Serious July 2016	1	0.903	0.953	−0.825	−0.754
Serious July 2015	0.880	1	0.720	−0.884	−0.682
Serious July 2016	0.903	1	0.824	−0.843	−0.801

Sources: Bowker-Chambers Mine Economics Data Base [14], Chambers-Bowker TSF Failures [5].

What emerges with more complete data on pre-2010 failures than we had in July 2015 and the additional six years of data (2010–2015) is an interesting, new view of the relative strength of correlations in the two high severity failure categories. Ore production is reaffirmed as the most dominant but with much higher correlations with both severity categories, 0.953 for Very Serious Failures and 0.824 for Serious Failures. Grade clearly emerges as much more dominant for Very Serious Failures and copper production cost (Cu Cost) emerges as much less important for Very Serious Failures and much more important for Serious Failures. Overall, there is more clarity on Serious Failures, and it is now apparent they are shaped by the same forces as Very Serious Failures.

As is clear in Figure 3, the rising trend of Very Serious Failures emerges despite the long-term offsetting effects of lower ore production unit costs that accompany the plunge in as-milled grades.

The World Bank noted this shift in the relationship between finished metals production and ore production as of 2000 [1]. As was previously mapped [8], that spread continued to widen through 2009 [4]. In the six years since 2009, the spread is even more pronounced, primarily as a result of an even steeper and faster decline in available ore grades that the industry neither foresaw nor prepared for. This increasing spread between metals production from mines and ore production needed to attain that level of production very clearly begins around 1990, almost a full decade before the start of the supercycle. See Figure 4. A closer look at what was happening to grades, in Figure 5, as prices rose over the supercycle reveals the key impetus for failure.

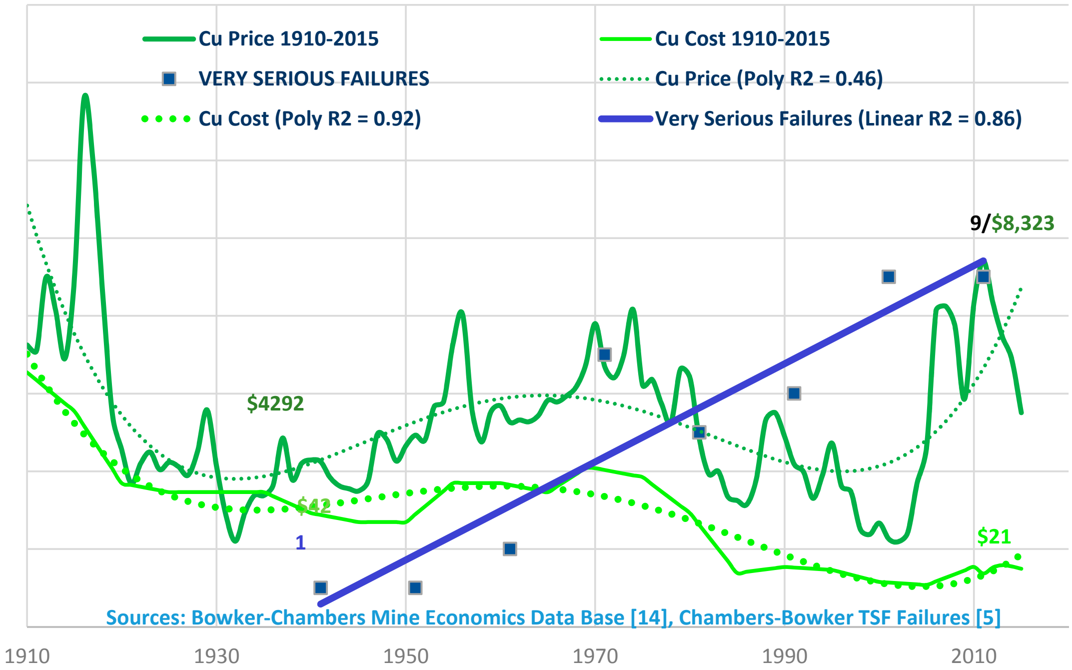

Figure 3. Failure trend increases despite lower costs & exponential price rises.

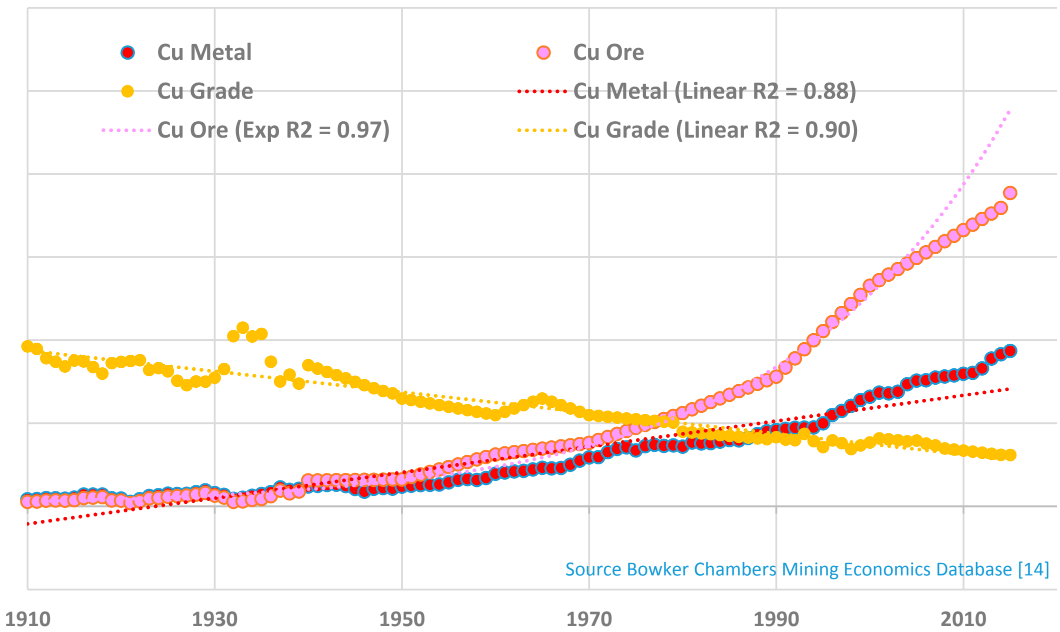

Figure 4. The shift in the mining metric from throughput to grade.

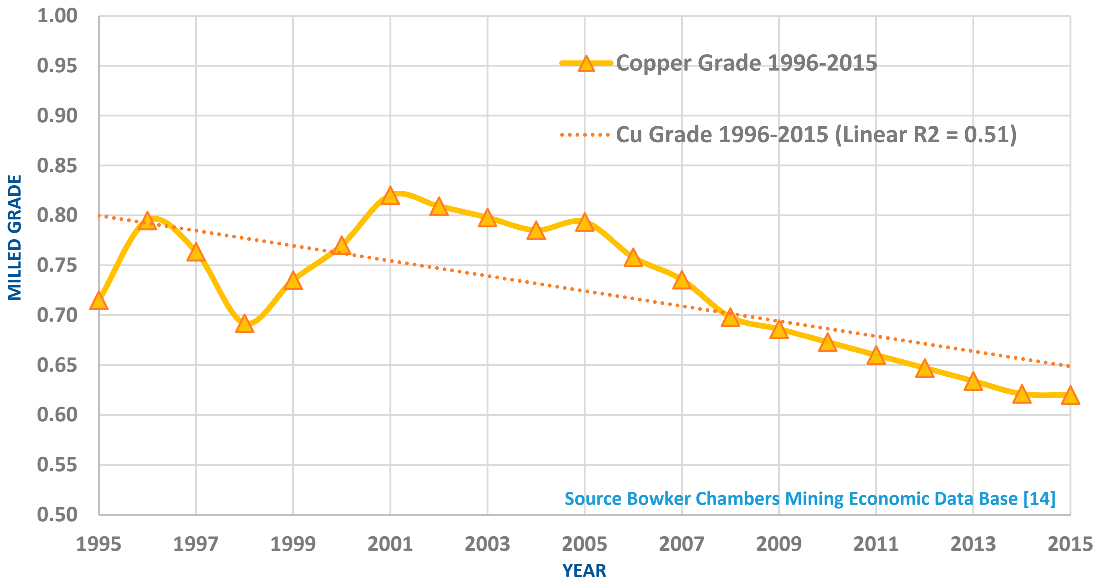

Figure 5. Global copper as-milled grade 1996–2015.

Over the entire period of the supercycle, as shown in Figure 5, "as milled" grades have dropped significantly, affecting not only smaller economically marginal mines but the behemoth Chilean and Top-40 producers as well.

As devised by ICOLD [23] and carried on by WISE [25], the tailings dam failures database captures no data on geological, geochemical or econometric descriptors of the mines with failed TSFs. The data on physical characteristics of the TSF facility (height, capacity, type of construction) and severity (run out release deaths) is sporadically reported, even for catastrophic failures. It has nevertheless been possible, with volunteer support from a colleague, to piece together some mine-level econometric markers on some of the mines with Very Serious Failures post 1990. The data on 7 of 18 mines with Very Serious Failures post 1996 strongly indicate that the econometric markers of these mines are significantly below global averages.

Average resource grade as of failure for the six mines which are primarily copper producers was 0.37 as compared with a global average head grade at producing copper mines of 0.76. Of 7 mines with Very Serious Failures 1992–2010, the Cu equivalent grade (i.e., taking account of other metals produced or translating all metals into Cu equivalent) was 1.10 as compared to a realized grade of 2.25, as reported by Aguirregabiria & Luengo [5] for their 330 producing copper mines, operating from 1992 to 2010. These are imperfect and non-exact comparisons, but they are also strongly persuasive that mines that produce Very Serious TSF Failures are poor performers viz. average global econometrics. This in turn suggests a significant public interest in giving independent authoritatively verified economic feasibility a specific and prominent place in mine and mine expansion approval, and in life-of-mine and life-of-facility regulatory oversight.

These adverse grade deviations at the mine-level translate to, and are determinant of, higher costs to produce, as well as of larger waste volumes per unit of metal produced.

The fundamentals of how this plays at the mine-level is simply and succinctly expressed by Andrey Dashkov, Senior Analyst, Casey Research: "*As a project moves to the development stage, the higher the grade, the more robust the projected economics of a project. For a mine in production, the higher the grade, the more technical sins and price fluctuations it can survive.*" [26]. Continuing in this analysis, Dashkov goes on to declare that volume and throughput (the Scholz foundation for profitability of low grade mines) is no longer king, and that grade is now king in determining which mines will be successful and which will fail. This was essentially validated by Bowker-Chambers [4] as the context and main driver in the emerging prevalence of catastrophic failures.

Dashkov's analysis is that a grade advantage is a critical determinant of ability to survive serious technical flubs and dramatic unpredictable price fluctuations. As a norm for all metals, this means that smaller, lower grade mines will suffer more and have more physical manifestations of their economic stress than larger, higher-grade mines. Very simply, smaller, lower grade mines operated by junior and midsize miners have less cushion. They must ride too close to the edge of financial viability viz. global metals markets and major producers to try to stay in production. They also have less access to high quality capital markets, paying more and operating under more onerous terms of credit than the top producers. George Ireland has frequently cited this factor as creating financial instability and uncertainty, when the due dates of credit do not match up with cash flow needs, expected revenue generation, and production capacities of the mine. This mismatch can actually lead to failure or involuntary investor takeover elevating uncertainty and instability [27].

In gold, as respected analyst Mark Fellows explains, a 10% fall in global average ore grade gives rise to a $50/oz. rise in average global production costs [28]. At the mine-level, a difference between a gold mine with 1.72 g/t and 2.2 g/t translates to a likely cost difference of $100/oz. in total production costs. These are the actual differences at the Gold Ridge mine, Guadalcanal, in 2009. This mine with complex anomalous ores never achieved profitability, not because of political unrest or weather, but because of the low quality and complexity of the deposit compared to others shaping world markets. Gold Ridge, with approximately 20 million cubic meters tailings storage capacity with a long history of many owners, frequent interruptions, and continually falling recovery rates (another emerging consequence of mining very low-grade ores), under ownership of landowners with limited technical competence, has hovered on the brink of complete failure by overtopping for two years [29]. While its resource grade is still 1.70 (or was when last studied for Allied by Golder in 2011, the best recovery rate Golder could project was 75% creating an effective (realizable grade) of only 1.4% [30]. That is still high compared to present global averages but the tailings problems have not been solved and the feasibility of actually re-entering production has not been assessed. The new owner, AXF, is a Chinese real estate company with no prior history or experience in mining [31].

3.8. Further Exploration of the Dimensionality of Relationship between Failures and Global Mining Economics

If the legal frameworks for mining mandated the maintenance of public information on the tailings facilities and their larger context of mine and miner on the mines they have approved (or are reviewing), it would be possible to directly compare mine-level with global economic profiles and develop proven failure risk markers that might help intercept the incubation of failure conditions early enough for correction before the failure occurs. This information does not exist in any permitting regime we have seen. We know from the mine-level narrative of catastrophic failures that poor vetting, shoestring economics, and production schedules ahead of safety were very much the key backstory at Mt Polley, which never attained economic feasibility. From the outset, Mt Polley was plagued by low grades and low recovery rates. A careful reading of all annual reports and of the NI 43-101 prepared by an in-house geologist indicates that the reopening in 2005 was based on sparse 4-year old data that was not independently verified or re-examined. Life of mine Average Cu Grade was 0.38 vs 0.70 global; higher throughput did not achieve higher metals output as recovery grades constantly were below expected. Imperial processed 29% more ore in 2013 as compared with 2006, its year of peak grade, but produced 3.2% less metal. As is obvious in Figure 6 falling grades parallel metals output. Life of mine to failure, the Very Serious failure rate for Mt Polley is 0.011 per million tonnes of ore to the mill vs 0.0004 globally, that is 27 times higher than the global failure performance.

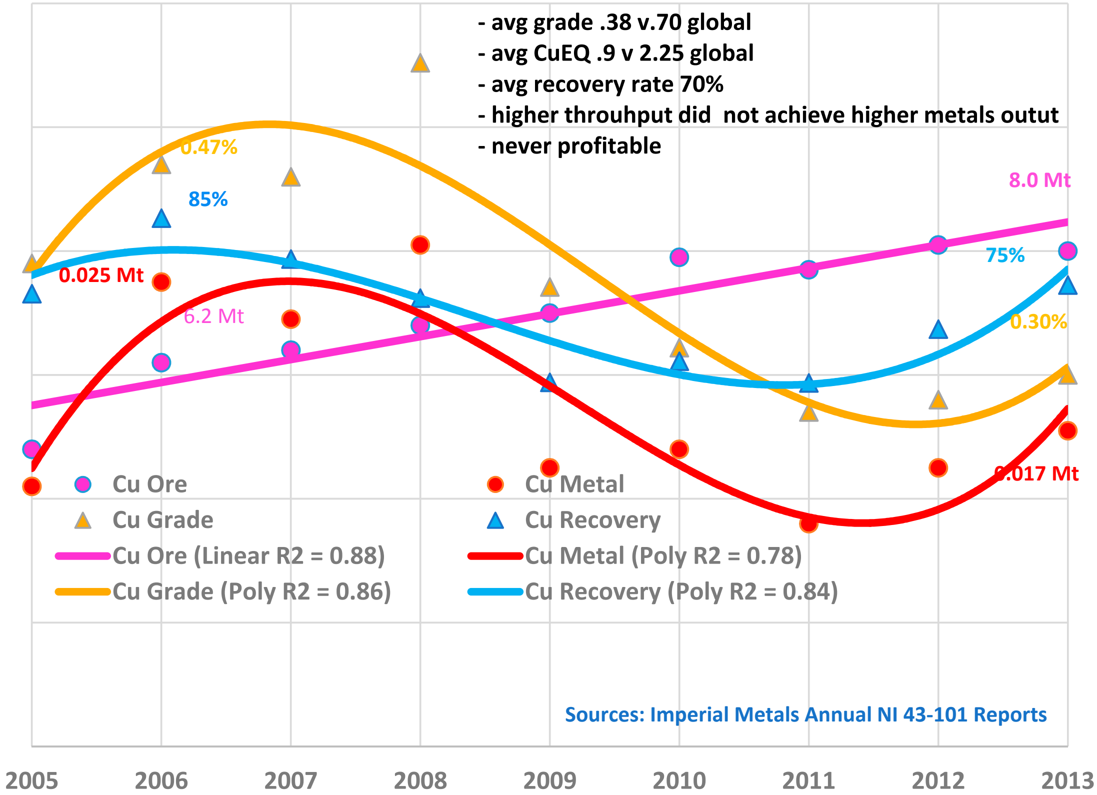

Figure 6. Mt Polley economics pre-failure.

The amount of debt Samarco had amassed for the 2010 expansion put great weight on them going forward. They did not stop to fix the Fundao dam or to create more long-term capacity onsite [5]. Piecing this economic back-story together for all failures into a database has so far been impossible. However, it is still possible to probe more deeply the dimensionality of the connection between failures and global economics over time at the aggregate level via Canonical Correlation Analysis (CCA). CCA is a way of exploring whether two data sets, in our case the failures data set and the global economics data set, are independent. It can also help identify the dimensions of cross influences or common unidentified external influences (e.g., technical incompetence, brain drain, improper application of technology, geographic shifts in production advantage, excessive debt lost productivity).

Prior research on failures 1940–2009 [4] utilizing CCA strongly indicated that TSF failures and copper economics data sets are interdependent, and this is reaffirmed with data through 2015 (see Database for technical documentation). More than 95% of the total variance is explained through the two canonical variables for both the pre-2010 and pre-2015 data sets. In both, extremely high eigenvalues (0.950 and 0.854), cumulatively explain 100% of the variation. These results strongly indicate the presence of a clear and powerful correlation between failures data and economics data that is linear in nature. The results also further suggest that there are no "missing variables" (no external latent variables commonly affecting both data sets). The Wilks Lambda variables for the entire CCA model for both pre-2010 (0.011) and post 2010 (0.007) data sets are extraordinarily low, supporting the assertion that the two data sets, failures and econometrics, are not independent.

What is most notable though over only 6 years (2010–2015) is the change in the composition of the canonical variables again pointing to the strong influence of grade, as shown in Table 4.

Table 4. Very Serious Failures correlations with Canonical Variables.

Variable	1940–2009	1936–2015
Copper Production (CUPROD)	−0.8285	−0.9136
Copper Grade (CUGRADE)	0.6064	0.8827
Copper Cost (CUCOST)	0.3982	0.5373

In the canonical variable most closely associated with Very Serious Failures, the correlations with the three mining economics variables is stronger for all 3 post 2010 v pre- 2010. The most dramatic change is with grade from 0.6064 pre- 2010, to 0.8827 post 2010.

The eigenvalues imply a very strong simple linear relationship between Very Serious Failures and both grade and ore production volume.

We undertook examination of these relationships through linear regression, again not to establish statistical significance but just to describe the relationships.

The regression of Very Serious Failures by grade explained 79% of the total variance as shown in Figure 7. Each blue dot is an actual observation. The chart shows the dispersion of observation with reference to the 95%confidence intervals. Again, this confirms the very strong influence of global average mill grade on catastrophic failures.

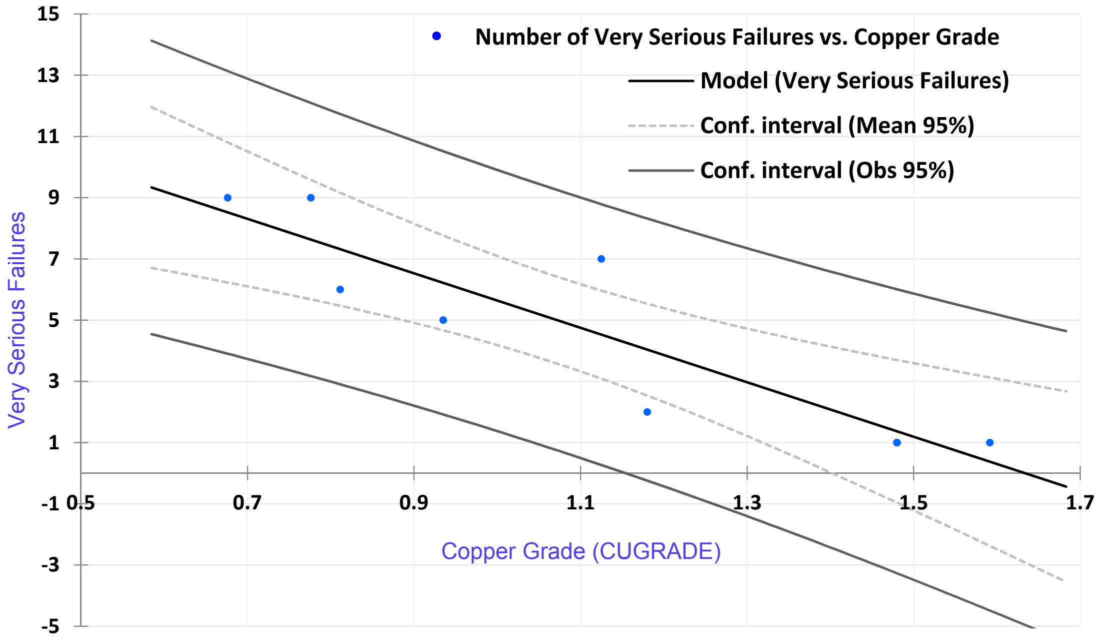

Figure 7. Regression of Very Serious Failures by CUGRADE (R^2 = 0.793).

The regression of Very Serious Failures by ore production volume (copper production—CUPROD), essentially tailings waste volume, explained 76% of total variance as shown in Figure 8.

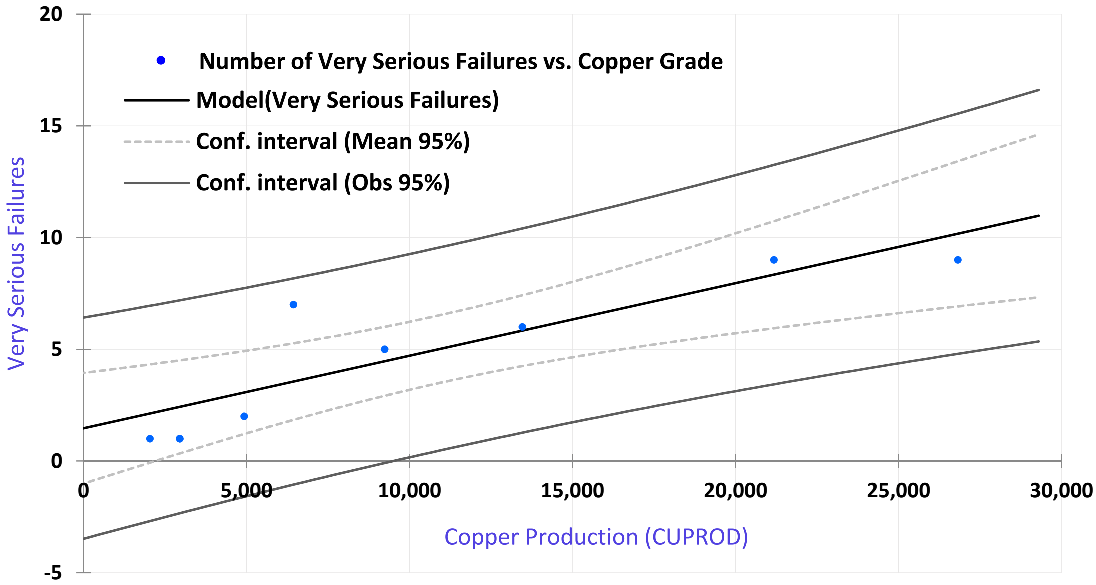

Figure 8. Regression of Very Serious Failures by copper production (R^2 = 0.764).

4. Conclusions

Overlaying the supercycle autopsies of some of the world's top mining analysts onto what we previously documented in Bowker-Chambers [3] explains the extent and nature of dysfunctions in global mine planning, development and operation that shaped what we previously had mapped and inferred from our data.

In their independent examination of the supercycle, there is a clear consensus among the world's top mining analysts that we have crossed the threshold into a new and as-yet unclear era of mining. If it is understood at all, the industry, its regulators and even its key investment analysts have not publicly recognized that present discovery and as milled grades have reached levels that are beyond presently known technology that had previously worked to create economic viability for low grade large scale mines. No regulatory agency known to us has recognized the need to reexamine the large-scale low-grade mining projects like KSM, Pebble, and PolyMet that were originated in the frenzy of the supercycle on assumptions that were never proven in the first instance, and which are very clearly no longer true. No regulatory agency known to us has recognized that the supercycle was a time of pushing marginal mines and their existing infrastructure beyond design capacity and that, as at Mt Polley and Samarco, those are practices in which failure incubates and matures.

Neither the industry itself nor its regulators are taking realistic account of the implications of the fact that somewhere between 1/3 and 1/2 of all technically operating mines are no longer economically viable or never were viable. Such a high incidence of stranded assets does not indicate wellness for the industry as a whole. Regulators passively stand by while the wholesale dumping of these mines continues assuming that production will resume, that jobs will be retained, and that new revenue will finance identification and correction of any potential flaws in infrastructure aggressively pushed into production levels beyond planned capacity. These are not assumptions supported by available data or expert economic analysis.

There is not enough data to say what percentage of these no longer viable mines have TSF's large enough to cause catastrophic failure, but we have confidence in our prediction methods which accurately predicted the 9 very serious failures 2006–2015. We have confidence that the fall out of the supercycle dysfunctions will manifest in higher than previously expected Serious and Very Serious Failures. The data and our proven method of prediction tell us that the expected number of high severity failures is greater than previously estimated for the decade 2010–2020, and that we can expect a record high of at least 15 in each high consequence category for 2016–2025.

We now can clearly see a significantly elevated and not fully examined global portfolio risk of failure. History itself proves that characterization wrong. We had pieced together a patchwork quilt of costs and legal judgments on post 1990 Very Serious failures predicting $6 billion in 11 Very Serious failures 2010–2020. Samarco alone has damages that exceed that hobbled together estimate by at least 3-fold from a TSF with only a capacity of only 60 Mm^3. We now reasonably anticipate 13 not 11 Very Serious failures and an additional 13 Serious Failures based on actual ore production volumes and compilation and reconciliation of independent expert predictions post 2015.

Portfolio Public Liability Risk is Not Going to Simply Self-Correct to Less Elevated Levels

Nether MAC nor ICMM nor any mining jurisdiction we are aware of has undertaken any reforms that will be effective in lowering public liability portfolio risk.

In risk management we live by that old adage "an ounce of prevention is worth a pound of cure". Waiting for revenue that will never come to fix broken and no longer serviceable infrastructure is not in the public interest. It offers neither prevention nor hope of cure for whatever already formed catastrophic losses are maturing to final event.

Continuing to advance and tout mega scale low-grade projects conceived in the supercycle and based on its cowboy economics offers no reform, no future with better outcomes.

Regulators have clearly chosen protection and support for the mining industry over reducing public risk and public liability. That, and past long-standing issues of enormous gravity, have brought a loud public backlash in anti-mining anger in the form of extreme and reactive legislation with outright complete prohibitions on all metallic mining, bans on open pit mining, bans of varying degrees on all upstream construction. In the case of Maine, a state with only two modern era mines, both failures with unresolved, unfunded, public consequence, recent legislative changes to mining law sponsored by a statewide coalition of non-governmental organizations requiring upfront payment in cash-equivalent for an independently verified worst-case scenario. This is the first evidence of reactive mining statutes in the United States and Canada since passage of Wisconsin's "Prove-It" statute, which most in the industry also regard as anti-mining.

If regulators and the industry do not address themselves more actively to public risk and public liability than they have done to date, three years after Mt Polley and two years after Samarco, it is reasonable to expect that elevated public outrage will spawn more of these public opinion-driven reactionary extreme anti-mining proposals.

While all that unfolds as it may, our data say the public liability risk continues to elevate and the consequence of failure continues to grow.

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Chronology of major tailings dam failures

(from 1960)

(last updated 8 July 2017)

Note: Due to limited availability of data, this compilation is in no way complete

Date	Location	Parent company	Ore type	Type of Incident	Release	Impacts
2017, June 30	Mishor Rotem, Israel	Rotem Amfert Negev Ltd., Israel Chemicals (ICL)	phosphate	phosphogypsum dam failure	100,000 cubic metres of acidic waste water	The toxic wastewater surged through the dry Ashalim riverbed and left a wake of ecological destruction more than 20 km long
2017, Mar. 12	Tonglvshan Mine, Hubei province, China	China Daye Non-Ferrous Metals Mining Limited	copper, gold, silver, iron	a partial dam failure occurred at the northwestern corner of the tailings pond, opening a crevasse (gap) of approx. 200 metres	approx. 200,000 cubic metres of tailings	The tailings flooded the fish pond downstream of approx. 27 hectares. Two persons were reported dead and one was reported missing.
2016, Aug. 27	New Wales plant, Mulberry, Polk County, Florida, USA	Mosaic Co	phosphate	a 14 metre-wide sinkhole appeared in a phosphogypsum stack, opening a pathway for contamined liquid into the underground; the liquid reached the Floridan Aquifer, a major drinking water resource	840,000 cubic metres of contaminated liquid released (as of Sep. 17, 2016)	
2016, Aug.	Dahegou Village, Luoyang, Henan	Luoyang Xiangjiang	bauxite	failure of a tailings dam	?	village totally submerged in

8	province, China	Wanji Aluminium Co., Ltd.		holding about 2 million cubic metres of red mud		red mud, around 300 villagers evacuated, many farm and domestic animals killed
2015, Nov. 21	Hpakant, Kachin state, Myanmar	?	jade	waste heap failure	?	at least 113 people killed
2015, Nov. 5	Germano mine, Bento Rodrigues, distrito de Mariana, Região Central, Minas Gerais, Brazil	Samarco Mineração S.A. (50% BHP Billiton, 50% Vale)	iron	failure of the Fundão tailings dam due to insufficient drainage, leading to liquefaction of the tailings sands shortly after a small earthquake. For details, see: The Fundão Tailings Dam Investigation	32 million m^3 Video of the flow slide	slurry wave flooded town of Bento Rodrigues, destroying 158 homes, at least 17 persons killed and 2 reported missing; slurry pollutes North Gualaxo River, Carmel River and Rio Doce over 663 km, destroying 15 square kilometers of land along the rivers and cutting residents off from potable water supply
2014, Sep. 10	Herculano mine, Itabirito, Região Central, Minas Gerais, Brazil	Herculano Mineração Ltda	iron	tailings dam failure	?	two workers killed and one missing
2014, Aug. 7	Buenavista del Cobre mine, Cananea, Sonora, Mexico	Southern Copper Corp. (Grupo México)	copper	tailings dam failure	40,000 m^3 of copper sulphate	flow into the 420km-long Bacanuchi river waterway, a tributary of the Sonora River, directly affecting 800,000 people
2014, Aug. 4	Mount Polley mine, near Likely, British Columbia, Canada	Imperial Metals Corp.	copper, gold	tailings dam failure due to foundation	7.3 million m^3 of tailings, 10.6 million m^3 of water, and 6.5	tailings flowing into adjacent Polley Lake

				failure (**view details**)	million m^3 of interstitial water	and, through Hazeltine Creek, into Quesnel Lake (Mitchell Bay)
2014, Feb. 2	Dan River Steam Station, Eden, North Carolina, USA	Duke Energy	coal ash	collapse of an old drainage pipe under a 27-acre ash waste pond	about 82,000 short tons [74,400 t] of toxic coal ash and 27 million gallons [100,000 m^3] of contaminated water	ash flowing through drainage pipe into Dan River
2013, Nov. 15-19	Zangezur Copper Molybdenum Combine, Kajaran, Syunik province, Armenia	Cronimet Mining AG	copper, molybdenum	damage of tailings pipeline	?	tailings flowing into Norashenik River for several days
2013, Oct. 31	Obed Mountain Coal Mine, northeast of Hinton, Alberta, Canada	Sherritt International	coal	breach of wall in containment pond	spill of 670,000 m^3 of coal wastewater and 90,000 tonnes of muddy sediment	plume of slurry containing fine coal particles, clay and heavy metals into the Apetowun und Plate creeks and eventually the Athabasca River
2012, Dec. 17	former Gullbridge mine site, Newfoundland, Canada		copper	embankment dam failure, width 50 m		non-consumption water advisory has been issued for the Town of South Brook (view details - Newfoundland and Labrador Department of Environment and Conservation)
2012, Nov. 4	Sotkamo, Kainuu province, Finland	Talvivaara Mining Company Plc	nickel, (uranium by-product planned)	leak from gypsum pond through a "funnel-shaped hole"	hundreds of thousands of cubic metres of contaminated waste water	nickel and zinc concentrations in nearby Snow River exceeded the values that are harmful to organisms tenfold or even

						a hundredfold, uranium concentrations more than tenfold (view details)
2011, Jul. 21	Mianyang City, Songpan County, Sichuan Province, China	Xichuan Minjiang Electrolytic Manganese Plant	manganese	tailings dam damaged from landslides caused from heavy rains	?	tailings damaged residential roads and houses, forcing 272 people to leave; tailings were washed into the Fujiang River, leaving 200,000 people without drinking water supply
2010, Oct. 4	Kolontár, Hungary (Aerial View: Google Maps)	MAL Magyar Alumínium	bauxite	tailings dam failure (**view details**)	700,000 cubic metres of caustic red mud	several towns flooded, 10 people killed, approx. 120 people injured, 8 square kilometres flooded
2010, Jun. 25	Huancavelica, Peru	Unidad Minera Caudalosa Chica	?	tailings dam failure	21,420 cubic metres of tailings	contamination of río Escalera and río Opamayo 110 km downstream
2009, Aug. 29	Karamken, Magadan region, Russia	Karamken Minerals Processing Plant	gold	tailings dam failure after heavy rain (see background info 2004, press compilation 2009, update 2012 - SRIC)	more than 1 million m^3 of water, 150,000 m^3 of tailings, and 55,000 m^3 of dams materials	eleven homes were carried away by the mudflow; at least one person was killed
2009, May 14	Huayuan County, Xiangxi Autonomous Prefecture, Hunan Province, China	?	manganese	tailings dam failure (capacity: 50,000 cubic metres)	?	The landslide set off by the tailings dam failure destroyed a home, killing three and

						injuring four people.
2008, Dec. 22	Kingston fossil plant, Harriman, Tennessee, USA	Tennessee Valley Authority	coal ash	retention wall failure	Release of 5.4 million cubic yards [4.1 million cubic metres] of ashy slurry	The ash slide covered 400 acres [1.6 square kilometres] as deep as 6 feet [1.83 metres]. The wave of ash and mud toppled power lines, covered Swan Pond Road and ruptured a gas line. It damaged 12 homes, and one person had to be rescued, though no one was seriously hurt.
2008, Sep. 8	Taoshi, Linfen City, Xiangfen county, Shanxi province, China	Tashan mining company	iron	Collapse of a waste-product reservoir at an illegal mine during rainfall	?	A mudslide several metres high buried a market, several homes and a three-storey building. At least 254 people are dead and 35 injured.
2007, Jan. 10	Miraí, Minas Gerais, Brazil	Mineração Rio Pomba Cataguases Ltda	bauxite	tailings dam failure after heavy rain	2 million m^3 of mud, containing water and clay ("red mud")	the mud flow left about 4000 residents of the cities of Miraí and Muriaé in the Zona da Mata homeless. Crops and pastures were destroyed and the water supply was compromised in cities in the states of Minas Gerais and Rio de Janeiro.

2006, Nov. 6	Nchanga, Chingola, Zambia	Konkola Copper Mines Plc (KCM) (51% Vedanta Resources plc)	copper	failure of tailings slurry pipeline from Nchanga tailings leaching plant to Muntimpa tailings dumps	?	Release of highly acidic tailings into Kafue river; high concentrations of copper, manganese, cobalt in river water; drinking water supply of downstream communities shut down
2006, April 30	near Miliang, Zhen'an County, Shangluo, Shaanxi Province, China	Zhen'an County Gold Mining Co. Ltd.	gold	tailings dam failure during sixth upraising of dam	?	The landslide buried about 40 rooms of nine households, leaving 17 residents missing. Five injured people were taken to hospital. More than 130 local residents have been evacuated. Toxic potassium cyanide was released into the Huashui river, contaminating it approx. 5 km downstream.
2005, April 14	Bangs Lake, Jackson County, Mississippi, USA	Mississippi Phosphates Corp.	phosphate	phosphogypsum stack failure, because the company was trying to increase the capacity of the pond at a faster rate than normal, according to Officials with the Mississippi Department of Environmental	approx. 17 million gallons of acidic liquid (64,350 m^3)	liquid poured into adjacent marsh lands, causing vegetation to die

				Quality (the company has blamed the spill on unusually heavy rainfall, though)		
2004, Nov. 30	Pinchi Lake, British Columbia, Canada	Teck Cominco Ltd.	mercury	tailings dam (100-metres long and 12-metres high) collapses during reclamation work	6,000 to 8,000 m^3 of rock, dirt and waste water	tailings spilled into 5,500 ha Pinchi Lake
2004, Sep. 5	Riverview, Florida, USA	Cargill Crop Nutrition	phosphate	a dike at the top of a 100-foot-high gypsum stack holding 150-million gallons of polluted water broke after waves driven by Hurricane Frances bashed the dike's southwest corner	60 million gallons (227,000 m^3) of acidic liquid	liquid spilled into Archie Creek that leads to Hillsborough Bay
2004, May 22	Partizansk, Primorski Krai, Russia	Dalenergo	coal ash	A ring dike, enclosing an area of roughly 1 km^2 and holding roughly 20 million cubic meters of coal ash, broke. The break left a hole roughly 50 meter wide in the dam.	approximately 160,000 cubic meters of ash	The ash flowed through a drainage canal into a tributary to the Partizanskaya River which empties in to Nahodka Bay in Primorski Krai (east of Vladivostok). For details download Sept. 2004 report (PDF) by Paul Robinson, SRIC
2004, March 20	Malvési, Aude, France	Comurhex (Cogéma/Areva)	decantation and evaporation pond of uranium conversion plant	dam failure after heavy rain in preceding year (view **details**)	30,000 cubic metres of liquid and slurries	release led to elevated nitrate concentrations of up to 170 mg/L in the canal of

						Tauran for several weeks
2003, Oct. 3	Cerro Negro, Petorca prov., Quinta region, Chile	Cia Minera Cerro Negro	copper	tailings dam failure	50,000 tonnes of tailings	tailings flowed 20 kilometers downstream the río La Ligua
2002, Aug. 27 / Sep. 11	San Marcelino, Zambales, Philippines	Dizon Copper Silver Mines, Inc.		overflow and spillway failure of two abandoned tailings dams after heavy rain (**view details**)	?	Aug. 27: some tailings spilled into Mapanuepe Lake and eventually into the Sto. Tomas River Sep. 11: low lying villages flooded with mine waste; 250 families evacuated; nobody reported hurt so far
2001, Jun. 22	Sebastião das Águas Claras, Nova Lima district, Minas Gerais, Brazil	Mineração Rio Verde Ltda	iron	mine waste dam failure (**view details**)	?	tailings wave traveled at least 6 km, killing at least two mine workers, three more workers are missing
2000, Oct. 18	Nandan county, Guangxi province, China	?	?	tailings dam failure	?	at least 15 people killed, 100 missing; more than 100 houses destroyed
2000, Oct. 11	Inez, Martin County, Kentucky, USA	Martin County Coal Corporation (100% A.T. Massey Coal Company, Inc., Richmond, VA (100% Fluor Corp.))	coal	tailings dam failure from collapse of an underground mine beneath the slurry impoundment (**view details**)	250 million gallons (950,000 m^3) of coal waste slurry released into local streams	About 75 miles (120 km) of rivers and streams turned an irridescent black, causing a fish kill along the Tug Fork of the Big Sandy River and some of its tributaries. Towns along

						the Tug were forced to turn off their drinking water intakes.
2000, Sep. 8	Aitik mine, Gällivare, Sweden	Boliden Ltd.	copper	tailings dam failure from insufficient perviousness of filter drain (**view details**)	release of 2.5 million m^3 of liquid into an adjacent settling pond, subsequent release of 1.5 million m^3 of water (carrying some residual slurry) from the settling pond into the environment	
2000, Mar. 10	Borsa, Romania	Remin S.A.		tailings dam failure after heavy rain	22,000 t of heavy-metal contaminated tailings	contamination of the Vaser stream, tributary of the Tisza River. View Romanian Govt. report · UNEP report (527k PDF)
2000, Jan. 30	Baia Mare, Romania	Aurul S.A. (Esmeralda Exploration, Australia (50%), Remin S.A. (44.8%))	gold recovery from old tailings	tailings dam crest failure after overflow caused from heavy rain and melting snow (**view details**)	100,000 m^3 of cyanide-contaminated liquid	contamination of the Somes/Szamos stream, tributary of the Tisza River, killing tonnes of fish and poisoning the drinking water of more than 2 million people in Hungary
1999, Apr. 26	Placer, Surigao del Norte, Philippines	Manila Mining Corp. (MMC)	gold	tailings spill from damaged concrete pipe	700,000 tonnes of cyanide tailings	17 homes buried, 51 hectares of riceland swamped
1998, Dec. 31	Huelva, Spain	Fertiberia, Foret	phosphate	dam failure during storm (view details)	50,000 m^3 of acidic and toxic water	
1998, Apr.	Los Frailes, Aznalcóllar, Spain	Boliden Ltd., Canada	zinc, lead, copper,	dam failure from foundation	4-5 million m^3	thousands of hectares of

25			silver	failure (**view details**)	of toxic water and slurry	farmland covered with slurry
1997, Dec. 7	Mulberry Phosphate, Polk County, Florida, USA	Mulberry Phosphates, Inc.	phosphate	phosphogypsum stack failure	200,000 m^3 of phosphogypsum process water	biota in the Alafia River eliminated
1997, Oct. 22	Pinto Valley, Arizona, USA	BHP Copper	copper	tailings dam slope failure	230,000 m^3 of tailings and mine rock	tailings flow covers 16 hectares
1996, Nov. 12	Amatista, Nazca, Peru	?	?	liquefaction failure of upstream-type tailings dam during earthquake	more than 300,000 m^3 of tailings	flow runout of about 600 meters, spill into river, croplands contaminated
1996, Aug. 29	El Porco, Bolivia	Comsur (62%), Rio Tinto (33%)	zinc, lead, silver	dam failure	400,000 tonnes	300 km of Pilcomayo river contaminated
1996, Mar. 24	Marcopper, Marinduque Island, Philippines	Placer Dome Inc., Canada (40%)	copper	Loss of tailings from storage pit through old drainage tunnel	1.6 million m^3	Evacuation of 1200 residents, 18 km of river channel filled with tailings, US$ 80 million damage
1995, Dec.	Golden Cross, New Zealand	Coeur d'Alène, Idaho, USA	gold	Dam movement of dam containing 3 million tonnes of tailings (continuing) (view details)	Nil (so far)	Nil (so far)
1995, Sep. 2	Placer, Surigao del Norte, Philippines	Manila Mining Corp.	gold	Dam foundation failure	50,000 m^3	12 people killed, coastal pollution
1995, Aug. 19	Omai, Guyana	Cambior Inc., Canada (65%), Golden Star Resources Inc., Colorado, USA (30%)	gold	tailings dam failure from internal dam erosion (preliminary report on technical causation)	4.2 million m^3 of cyanide slurry	80 km of Essequibo River declared environmental disaster zone (view details)
1994, Nov. 19	Hopewell Mine, Hillsborough County, Florida, USA	IMC-Agrico	phosphate	dam failure	Nearly 1.9 million m^3 of water from a	spill into nearby wetlands and the Alafia

					clay settling pond	River, Keysville flooded
1994, Oct. 2	Payne Creek Mine, Polk County, Florida, USA	IMC-Agrico	phosphate	dam failure	6.8 million m^3 of water from a clay settling pond	majority of spill contained on adjacent mining area; 500,000 m^3 released into Hickey Branch, a tributary of Payne Creek
1994, Oct.	Fort Meade, Florida, USA	Cargill	phosphate	?	76,000 m^3 of water	spill into Peace River near Fort Meade
1994, June	IMC-Agrico, Florida, USA	IMC-Agrico	phosphate	Sinkhole opens in phosphogypsum stake	?	Release of gympsum and water into groundwater
1994, Feb. 22	Harmony, Merriespruit, South Africa	Harmony Gold Mines	gold	Dam wall breach following heavy rain	600,000 m^3	tailings traveled 4 km downstream, 17 people killed, extensive damage to residential township
1994, Feb. 14	Olympic Dam, Roxby Downs, South Australia	WMC Ltd.	copper, uranium	leakage of tailings dam during 2 years or more	release of up to 5 million m^3 of contaminated water into subsoil	?
1993, Oct.	Gibsonton, Florida, USA	Cargill	phosphate	?	?	Fish killed when acidic water spilled into Archie Creek
1993	Marsa, Peru	Marsa Mining Corp.	gold	dam failure from overtopping	?	6 people killed
1992, Mar. 1	Maritsa Istok 1, near Stara Zagora, Bulgaria	?	ash/cinder	dam failure from inundation of the beach	500,000 m^3	?
1992, Jan.	No.2 tailings pond, Padcal, Luzon, Philippines	Philex Mining Corp.	copper	Collapse of dam wall	80 million tonnes	?

				(foundation failure)		
1991, Aug. 23	Sullivan mine, Kimberley, British Columbia, Canada	Cominco Ltd	lead/zinc	dam failure (liquefaction in old tailings foundation during construction of incremental raise)	75,000 m^3	the slided material was contained in an adjacent pond
1989, Aug. 25	Stancil, Perryville, Maryland, USA	?	sand and gravel	dam failure during capping of the tailings after heavy rain	38,000 m^3	tailings flowside covered 5000 m2
1988, Apr. 30	Jinduicheng, Shaanxi province, China	?	molybdenum	breach of dam wall (spillway blockage caused pond level to rise too high)	700,000 m^3	approx. 20 people killed
1988, Jan. 19	Tennessee Consolidated No.1, Grays Creek, TN, USA	Tennessee Consolidated Coal Co.	coal	dam wall failure from internal erosion, caused from failure of an abandoned outlet pipe	250,000 m^3	?
1988	Riverview, Florida, USA	Gardinier (now Cargill)	phosphate	?	acidic spill	Thousands of fish killed at mouth of Alafia River
1987, April 8	Montcoal No.7, Raleigh County, West Virginia, USA	Peabody Coal Co. (now Peabody Energy)	coal	dam failure after spillway pipe breach	87,000 cubic meters of water and slurry	tailings flow 80 km downstream
1986, May	Itabirito, Minas Gerais, Brazil	Itaminos Comercio de Minerios	?	dam wall burst	100,000 tonnes	tailings flow 12 km downstream
1986	Huangmeishan, China	?	iron	dam failure from seepage/slope instability	?	19 people killed
1985, July 19	Stava, Trento, Italy	Prealpi Mineraia	fluorite	dam failure, caused from insufficient safety margins and inadequate decant pipe construction (**view details**)	200,000 m^3	tailings flow 4.2 km downstream at 90 km/h; 268 people killed, 62 buildings destroyed (**view details**)

1985, Mar. 3	Veta de Agua No.1, Chile	?	copper	dam wall failure, due to liquefaction during earthquake	280,000 m^3	tailings flow 5 km downstream
1985, Mar. 3	Cerro Negro No.4, Chile	Cia Minera Cerro Negro	copper	dam wall failure, due to liquefaction during earthquake	500,000 m^3	tailings flow 8 km downstream
1985	Olinghouse, Wadsworth, Nevada, USA	Olinghouse Mining Co.	gold	embankment collapse from saturation	25,000 m^3	tailings flow 1.5 km downstream
1982, Nov. 8	Sipalay, Negros Occidental, Philippines	Marinduque Mining and Industrial Corp.	copper	dam failure, due to slippage of foundations on clayey soils	28 million tonnes	widespread inundation of agricultural land up to 1.5 m high
1981, Dec. 18	Ages, Harlan County, Kentucky, USA	Eastover Mining Co.	coal	dam failure after heavy rain	96,000 m^3 coal refuse slurry	the slurry wave traveled the Left Fork of Ages Creek 1.3 km downstream, 1 person was killed, 3 homes destroyed, 30 homes damaged, fish kill in Clover Fork of the Cumberland River
1981, Jan. 20	Balka Chuficheva, Lebedinsky, Russia	?	iron	dam failure	3.5 million m^3	tailings travel distance 1.3 km
1980, Oct. 13	Tyrone, New Mexico, USA	Phelps Dodge	copper	dam wall breach, due to rapid increase in dam wall height, causing high internal pore pressure	2 million m^3	tailings flow 8 km downstream and inundate farmland
1979, July 16	Church Rock, New Mexico, USA	United Nuclear	uranium	dam wall breach, due to differential foundation settlement	370,000 m^3 of radioactive water, 1,000 tonnes of contaminated sediment	Contamination of Rio Puerco sediments up to 110 km downstream

1979 or earlier	(unidentified), British Columbia, Canada	?	?	piping in the sand beach of the tailings dam	40,000 m^3 of ponded water	considerable property damage
1978, Jan. 31	Arcturus, Zimbabwe	Corsyn Consolidated Mines	gold	slurry overflow after continuous rain over several days	30,000 tonnes	1 person killed, extensive siltation to waterway and adjoining rough pasture
1978, Jan. 14	Mochikoshi No.1, Japan	Mochikoshi Gold Mining Company	gold	dam failure, due to liquefaction during earthquake	80,000 m^3	1 person killed, tailings flow 7-8 km downstream
1977, Feb. 1	Homestake, Milan, New Mexico, USA	Homestake Mining Company	uranium	dam failure, due to rupture of plugged slurry pipeline	30,000 m^3	no impacts outside the mine site
1976, Mar. 1	Zlevoto, Yugoslavia	?	lead, zinc	dam failure, due to high phreatic surface and seepage breakout on the embankment face	300,000 m^3	tailings flow reached and polluted nearby river
1975, June	Silverton, Colorado, USA	?	(metal)	dam failure	116,000 tonnes	tailings flow slide polluted nearly 100 miles (160 km) of the Animas river and its tributaries; severe property damage; no injuries
1975, Apr.	Madjarevo, Bulgaria	?	lead, zinc, gold	rising of tailings above design level caused overloading of the decant tower and collectors	250,000 m^3	?
1975	Mike Horse, Montana, USA	?	lead, zinc	dam failure after heavy rain	150,000 m^3	?
1974, Nov. 11	Bafokeng, South Africa	?	platinum	embankment failure by concentrated seepage and	3 million m^3	12 people killed in a mine shaft inundated by the tailings;

				piping through cracks		tailings flow 45 km downstream
1974, Jun. 1	Deneen Mica, North Carolina, USA	?	mica	dam failure after heavy rain	38,000 m^3	tailings released to an adjacent river
1973	(unidentified), Southwestern USA	?	copper	dam failure from increased pore pressure during construction of incremental raise	170,000 m^3	tailings traveled 25 km downstream
1972, Feb. 26	Buffalo Creek, West Virginia, USA	Pittston Coal	coal	collapse of tailings dam after heavy rain (view Citizens' Commission report)	500,000 m^3	the tailings traveled 27 km downstream, 125 people lost their lives, 500 homes were destroyed. Property and highway damage exceeded $65 million. (see details)
1971, Dec. 3	Fort Meade, Florida, USA	Cities Service Co.	phosphate	Clay pond dam failure, cause unknown	9 million m^3 of clay water	tailings traveled 120 km downstream with Peace River, large fish kill
1970	Mufulira, Zambia	?	copper	liquefaction of tailings, flowing into underground workings	some 1 million tons	89 miners killed
1970	Maggie Pie, United Kingdom	?	china clay	dam failure after raising the embankment and after heavy rain	15,000 m^3	tailings spilled 35 meters downstream
1969 or earlier	Bilbao, Spain	?	?	dam failure (liquefaction) after heavy rain	115,000 m^3	major downstream damage and loss of life
1968	Hokkaido, Japan	?	?	dam failure (liquefaction)	90,000 m^3	tailings traveled 150

				during earthquake		meters downstream
1967, Mar.	Fort Meade, Florida, USA	Mobil Chemical	phosphate	dam failure, no details available	250,000 m^3 of phosphatic clay slimes, 1.8 million m^3 of water	spill reaches Peace River, fish kill reported
1967	(unidentified), United Kingdom	?	coal	dam failure during regrading operations	?	tailings flow covered an area of 4 hectares
1966	(unidentified), East Texas, USA	?	gypsum	dam failure	76,000 - 130,000 m^3 of gypsum	flow slide traveled 300 meters; no fatalities
1966	Derbyshire, United Kingdom	?	coal	dam failure from foundation failure	30,000 m^3	tailings traveled 100 meters downstream
1966, Oct. 21	Aberfan, Wales, United Kingdom	Merthyr Vale Colliery	coal	dam failure (liquefaction) from heavy rain	162,000 m^3	the tailings traveled 600 meters, 144 people were killed (**view details**, watch video)
1966, Oct. 9	Geising/Erzgebirge, German Democratic Republic	VEB Zinnerz	tin	collapse of stream deviation tunnel located under the Tiefenbachtal tailings dam	70,000 m^3	the iron oxide slurry reached the Müglitz river and then the Elbe river, coloring it red until Hamburg
1966, May 1	Mir mine, Sgorigrad, Bulgaria	?	lead, zinc, copper, silver, (uranium?)	dam failure from rising pond level after heavy rains and/or failure of diversion channel	450,000 m^3	the tailings wave traveled 8 km to the city of Vratza and destroyed half of Sgorigrad village 1 km downstream, killing 488 people. (View **details** · historic photographs)
1965,	Bellavista, Chile	?	copper	dam failure	70,000 m^3	tailings

Mar. 28				during earthquake		traveled 800 meters downstream
1965, Mar. 28	Cerro Negro No.3, Chile	?	copper	dam failure during earthquake	85,000 m^3	tailings traveled 5 km downstream
1965, Mar. 28	El Cobre New Dam, Chile	?	copper	dam failure (liquefaction) during earthquake	350,000 m^3	tailings traveled 12 km downstream, destroyed the town of El Cobre and killed more than 200 people
1965, Mar. 28	El Cobre Old Dam, Chile	?	copper	dam failure (liquefaction) during earthquake	1.9 million m^3	
1965, Mar. 28	La Patagua New Dam, Chile	?	copper	dam failure (liquefaction) during earthquake	35,000 m^3	tailings traveled 5 km downstream
1965, Mar. 28	Los Maquis, Chile	?	copper	dam failure (liquefaction) during earthquake	21,000 m^3	tailings traveled 5 km downstream
1965	Tymawr, United Kingdom	?	coal	dam failure from overtopping	?	tailings traveled 700 meters downstream, causing considerable damage
1962	(unidentified), Peru	?	?	dam failure (liquefaction) during earthquake and after heavy rainfall	?	?
1961	Tymawr, United Kingdom	?	coal	dam failure, no details available	?	tailings traveled 800 meters downstream

tonnes = metric tonnes

Sources:

- **Tailings Dam Incidents**, U.S. Committee on Large Dams - USCOLD, Denver, Colorado, ISBN 1-884575-03-X, 1994, 82 pages *[compilation and analysis of 185 tailings dam incidents]*
- **Environmental and Safety Incidents concerning Tailings Dams at Mines**: Results of a Survey for the years 1980-1996 by Mining Journal Research Services; a report prepared for United Nations Environment Programme, Industry and Environment. Paris, 1996, 129 pages *[compilation of 37 tailings dam incidents]*

- **Tailings Dams - Risk of Dangerous Occurrences, Lessons learnt from practical experiences**, Bulletin 121, Published by United Nations Environmental Programme (UNEP) Division of Technology, Industry and Economics (DTIE) and International Commission on Large Dams (ICOLD), Paris 2001, 144 p. *[compilation of 221 tailings dam incidents mainly from the above two publications, and examples of effective remedial measures]*

and many others.

> See also: Chronology of uranium tailings dam failures

A compilation comprising many more tailings dam failures can be found here:
> Download: **The Risk, Public Liability, & Economics Of Tailings Storage Facility Failures**, by Lindsay Newland Bowker and David M. Chambers, July 21, 2015 (748kB PDF)

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PUBLICATIONS

A Win For The Mining Industry: EPA Declines To Impose CERCLA 108(b) Financial Responsibility Requirements

December 4, 2017

On December 1, 2017, the U.S. Environmental Protection Agency (EPA) released a pre-publication version of a final rule determining that imposing CERCLA 108(b) financial responsibility requirements on the hardrock mining industry was unwarranted.[1] The Final Rule satisfies a court-ordered timeline and rejects a proposed rule, published in January 2017,[2] which proposed regulations imposing CERCLA 108(b) financial responsibility requirements on operators of hardrock mining facilities. Based on information provided during the public comment period and EPA's re-evaluation of the rulemaking record, EPA determined that finalizing the proposed rule and establishing financial responsibility requirements for the industry was inappropriate because:

"the degree and duration of risk associated with the modern production, transportation, treatment, storage or disposal of hazardous substances by the hardrock mining industry does not present a level of risk of taxpayer funded response actions that warrant imposition of financial responsibility requirements."[3]

EPA's decision is significant for the mining industry, as EPA had estimated that the proposed rule would cost the industry approximately $111-171 million to address an estimated $15 million in unfunded clean-up costs, annually.[4]

Background

CERCLA Section 108(b), originally enacted in 1980, provides EPA the authority to require that "classes of facilities establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances."[5] It also required EPA to "identify those classes for which requirements will be first developed" by December 1983 and that "[p]riority in the development of such requirements shall be accorded to those facilities, owners, and operators which [EPA] determines present the highest risk of injury."[6] This deadline was never met.

In 2008, several environmental organizations sued to require EPA to publish the required priority notice and the U.S. District Court for the District of Northern California ordered EPA to identify the priority classes of facilities.[7] In July 2009, EPA published a Priority Notice in the Federal Register identifying classes of facilities in the hardrock mining industry sector as the first classes for which financial responsibility requirements would be developed. EPA also determined that classes of facilities in the chemical manufacturing, petroleum and coal products manufacturing, and electric power generation, transmission and distribution industries would be next in line for development of CERCLA 108(b) financial responsibility requirements.[8]

Five years later, EPA had not developed a rulemaking proposal, and environmental organizations returned to court to require EPA to proceed with the CERCLA 108(b) rulemaking. In January 2016, the D.C. Circuit approved a consent decree that established a schedule under which EPA would proceed with the CERCLA 108(b) rulemaking and publish a proposed rule by Dec. 1, 2016, and a final rule by Dec. 1, 2017.[9]

Accordingly, In December 2016, EPA released its proposed rule requiring facilities in the hardrock mining industry to establish and maintain evidence of financial responsibility.[10] The proposed rule included general requirements regarding the instruments that could be used to demonstrate financial responsibility under CERCLA 108(b) and specific regulations for applying CERCLA 108(b) financial responsibility requirements to the hardrock mining industry.[11] Industry, states, and other federal agencies that regulate the hardrock mining industry submitted comments on the proposed rule urging EPA not to finalize the proposed rule. A common theme in many of these comments was that EPA's evaluation of risk presented by the industry failed to account for the realities of modern mining practices and existing state and federal regulation, including reclamation bonding requirements, of the industry.

Final Rule

The Final Rule released on December 1, 2017, states that "EPA is not requiring evidence of financial responsibility under section 108(b) at hardrock mining facilities."[12] To support its decision, EPA determined that "the rulemaking record it assembled [for the Proposed Rule] does not support imposing financial responsibility requirements under section 108(b) on current hardrock mining operations."[13] EPA also stated that the proposed rule's assessment of risk "did not adequately consider the degree to which existing federal and state regulatory programs and improved mining practices at modern mines reduce the risk that there would be unfunded response liabilities at currently operating mines."[14]

In addition to determining that CERCLA 108(b) financial responsibility requirements for the hardrock mining industry are unwarranted, EPA also declined to finalize the general regulatory provisions regarding CERCLA 108(b) financial responsibility instruments, which were included in the proposed rule.[15] EPA justifies this decision because "there is no need to issue final requirements [regarding financial responsibility instruments] at this time as they would not be applicable to any classes of facilities until such time as final section 108(b) regulations applicable to classes of facilities are issued."[16]

Impact of Final Rule

While the release of the Final Rule is significant for the mining industry, it is unlikely that EPA's Final Rule will go unchallenged. Environmental groups have already indicated their intention to seek judicial review of EPA's Final Rule.[17]

In addition, this Final Rule and the expected challenges are likely to have a significant impact on the rulemakings to consider CERCLA 108(b) financial responsibility requirements for the chemical manufacturing, petroleum and coal product manufacturing, and electricity generation, transmission and distribution industries. EPA had committed to an aggressive rulemaking schedule to evaluate these industries and develop CERCLA 108(b) requirements, if necessary.[18] EPA's decision regarding hardrock mining provides a great deal of insight into how they might approach financial responsibility requirements for these other industries.

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[1] Final Rule: Financial Responsibility Requirements under CERCLA Section 108(b) for Classes of Facilities in the Hardrock Mining Industry, EPA-HQ-SFUND-2015-0781, Pre-Publication Copy (Dec. 1, 2017).

[2] Proposed Rule: Financial Responsibility Requirements under CERCLA Section 108(b) for Classes of Facilities in the Hardrock Mining Industry, 82 Fed. Reg. 3,388 (Jan. 11, 2017).

[3] Final Rule, at 47.

[4] *Id*. at 7.

[5] 42 U.S.C. § 9608(b)(1). The President has delegated his authority under CERCLA 108(b) to the EPA.

[6] *Id*.

[7] *Sierra Club, et al. v. Johnson*, No. 08-01409.

[8] Identification of Additional Classes of Facilities for Development of Financial Responsibility Requirements under CERCLA 108(b), 75 Fed. Reg. 816 (Jan. 6, 2010).

[9] *In re: Idaho Conservation League et al*., No. 14-1149.

[10] 82 Fed. Reg. 3,388.

[11] *Id*.

[12] Final Rule, at 9.

[13] *Id*. at 7.

[14] *Id*.

[15] *Id*. at 101.

[16] *Id*.

[17] Suzanne Featherston, *EPA says no to final Superfund rules*, Elko Daily Free Press (Dec. 1, 2017).

[18] Notice of Intent to Proceed with Rulemakings: Financial Responsibility Requirements for Facilities in the Chemical, Petroleum, and Electric Power Industries, 82 Fed. Reg. 3,512.

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CERCLA Section 108(b) Financial Responsibility

A public webinar hosted by the United States Environmental Protection Agency

May 17, 2016

Presentation Overview

- Background: CERCLA Section 108(b) Financial Responsibility (FR)
- CERCLA Section 108(b) Financial Responsibility Proposed Rule Structure
  - Universe of Facilities to be Regulated
  - Flow of Funds from the Financial Responsibility Instrument to the CERCLA Cleanup
  - Financial Responsibility Scope and Amount
  - Relationship of Section 108(b) Financial Responsibility to State, Tribal, and Local Government Law
  - Relationship of Section 108(b) Financial Responsibility to Other Federal Law
- Outreach Activities
- How to comment on the rule

Background: CERCLA Section 108(b) Financial Responsibility

- CERCLA is an acronym for the Comprehensive Environmental Response, Compensation and Liability Act of 1980. The law is also called "Superfund."
- During this webinar we will refer to this law as "CERCLA."
- Section 108(b) of CERCLA directs EPA to develop requirements that classes of facilities establish and maintain evidence of financial responsibility consistent with the degree and duration of risk associated with the production, transportation, treatment, storage, or disposal of hazardous substances.
- A key purpose of this provision is to assure that owners and operators make financial arrangements to address risks from the hazardous substances at their sites.
  - EPA also intends for the rule to create financial incentives for improved mining practices that reduce financial responsibility costs where existing practices ultimately may also help reduce risks and costs to the Superfund program.

Background: CERCLA Section 108(b) Financial Responsibility (cont.)

- Section 108(b) also requires that EPA issue a *Federal Register* notice identifying the classes of facilities for which it will first develop requirements.
- EPA issued that "Priority Notice" on July 28, 2009, and identified classes of facilities within the hardrock mining industry as those for which it would first develop requirements.
- https://www.epa.gov/superfund/superfund-financial-responsibility

Background: CERCLA Section 108(b) Financial Responsibility (cont.)

- For purposes of the notice, EPA defined “hardrock mining” as the extraction, beneficiation, or processing of metals (e.g., copper, gold, iron, lead, magnesium, molybdenum, silver, uranium, and zinc) and nonmetallic, non-fuel minerals (e.g., asbestos, phosphate rock, and sulfur).
- EPA also identified some classes of facilities that are not included in the rulemaking even though they fell within the above definition of “hardrock mining.” (See *Memorandum to The Record* entitled *“Mining Classes not Included in Identified Hardrock Mining Classes of Facilities”*, Dated June 29, 2009, EPA-HQ-SFUND-2009-0265-0033).

Background: CERCLA Section 108(b) Financial Responsibility (cont.)

- On January 29, 2016, the U.S. Court of Appeals for the District of Columbia Circuit issued an order establishing a schedule for EPA proceedings under CERCLA 108(b).
- The order requires EPA to sign a notice of proposed rulemaking for the hardrock mining industry by December 1, 2016, and to take final action by December 1, 2017.
- The order also requires EPA to make a determination on whether the Agency will issue a notice of proposed rulemaking on the (a) chemical manufacturing industry; (b) petroleum and coal products manufacturing industry; and (c) electric power generation, transmission, and distribution industry by December 1, 2016.

CERCLA 108(b) Financial Responsibility Proposed Rule Structure

Regulatory Approach Premises

EPA's Section 108(b) rulemaking approach under consideration proceeds from two premises:

- CERCLA is a response program that addresses CERCLA Section 107 liabilities - response costs, natural resource damages (NRD), and health assessments - and is distinct from closure and reclamation requirements of federal and state permit programs.
- Section 108(b) rules complement, but do not change or substitute for, existing Superfund cost recovery and enforcement procedures.

CERCLA 108(b) Financial Responsibility Proposed Rule Structure (cont.)

The regulatory approach under consideration is based on five foundational components:

- Universe of facilities to be regulated;
- Flow of funds from the financial responsibility instrument to the CERCLA cleanup;
- Financial responsibility scope and amount;
- Relationship of Section 108(b) financial responsibility to state, tribal, and local government law; and
- Relationship of Section 108(b) financial responsibility to other federal law.

A Preliminary Clarification: What the Rule Does *Not Do*

- EPA's proposed section 108(b) regulations will be stand-alone financial responsibility requirements. There are significant differences between these requirements and other existing requirements for hardrock mining facilities. In particular:
  - the proposed rule does *not* include technical requirements regulating the operation, closure, or reclamation of hardrock mining facilities; and
  - the proposed rule does *not* provide financial responsibility to ensure closure or reclamation requirements made applicable to hardrock mining facilities through a permit
- In addition:
  - By promulgating and implementing this regulation, EPA is *not* determining that a CERCLA response is required at a regulated facility.
  - CERCLA liability is unaffected by an owner or operator providing evidence of financial responsibility under EPA's CERCLA 108(b) regulations.

Universe of Facilities to be Regulated

- EPA has examined the mining facilities identified in the July 28, 2009 *Priority Notice* to identify classes for financial responsibility regulation.
- EPA is considering an approach that would identify classes of hardrock mines that the Agency believes present a lower level of risk of injury and would not, therefore, be included in the rulemaking. Classes the agency is considering not including in the rulemaking are:
  - placer mines that do not use hazardous substances;
  - exploration mines; and
  - small mines (less than five acres).
- Under this approach, the remainder of the hardrock mines identified in the Priority Notice would be included in the rulemaking.
- EPA would also include in the proposed rule primary processing activities located at or near the mine site that are under the same operational control as a regulated mine.

Flow of Funds from the Financial Responsibility Instrument to the CERCLA Cleanup

EPA evaluated how the Section 108(b) financial responsibility would supplement existing CERCLA sources of funding to address releases and potential releases of hazardous substances. Under the approach EPA is considering:

- Instruments that could be used to pay into a special account for a CERCLA settlement, into a trust fund established pursuant to an administrative order, or after a court finding of CERCLA liability.
- EPA would use existing Superfund enforcement processes first (settlements, orders, and cost recovery actions against potentially responsible parties) to effect clean up.
- Other parties (i.e., other federal agencies, the states, tribes, the public) could also make claims against the owner or operator under Section 107, payable from the instruments.
- Under CERCLA Section 108(c), parties (including EPA) could also bring a “direct action” claim against the instrument provider.

Financial Responsibility Scope and Amount

- EPA considered what Superfund costs should be covered by the financial responsibility instruments, and how the amount of financial responsibility should be determined.
- EPA is considering an approach under which owners and operators would be required to establish and maintain financial responsibility instruments to cover all Section 107 liabilities – response costs, natural resource damages, and covered health assessment costs - at their facilities.

Financial Responsibility Scope and Amount (cont.)

- To determine the amount of financial responsibility required for response costs, the Agency is developing a formula that would identify an amount of financial responsibility to reflect the primary site conditions and characteristics that would affect the costs of removal or remedial action.
- The formula would assign dollar values for a facility based on facility and unit characteristics (e.g., open pits; waste rock; tailings; heap leach; process ponds; water management; and, operations, maintenance, and monitoring).
- Dollar values would be summed to establish the facility's level of financial responsibility.

Financial Responsibility Scope and Amount (cont.)

- EPA intends the formula to reflect the relative risk of facility practices in managing hazardous substances, including reductions in risk that may result from compliance with other regulatory requirements.
- The Agency is considering a fixed amount of financial responsibility for health assessment costs and a fixed percent for natural resource damages, that would be required at all facilities.
- The total amount of funds would be available for any future response action, natural resource damages, or health assessment. Availability would not be tied to particular site features and would not in any way be driven by components of the formula.

Financial Responsibility Scope and Amount - HRM Financial Responsibility Formula

- Under the approach EPA is considering, facility-specific inputs would be used to generate a baseline level of financial responsibility.
- The baseline could then be reduced through demonstrating that current controls at the facility are in place.
- EPA anticipates that the formula will need to be reapplied periodically to account for changed facility conditions.

HRM Financial Responsibility Formula: Categories

- EPA has identified several categories it is currently analyzing to obtain statistically-derived factors for use in the formula, including components:
  - Associated with particular sources and controls
    - Includes open pits, underground mines, waste rock piles, heap/dump leaches, tailings facilities, process ponds and reservoirs, and slag piles
  - Associated with site-wide sources and controls
    - Drainage construction
    - Solid and hazardous waste disposal
  - Associated with operations and maintenance (O&M)
    - Interim water management and long-term water treatment
    - Site-wide O&M and monitoring

HRM Financial Responsibility Formula: Examples of Expected Formula Inputs

- EPA is looking at **current** site features as the basis for inputs which an owner or operator will enter to calculate the baseline amount
- The site features are both readily identifiable by the facility owner or operator, and readily verifiable by the EPA
  - Acreage of site features (e.g., waste rock acreage)
  - Presence of an underground mine
  - Hydraulic head in the underground mine
  - Distance to surface water
  - Net precipitation (i.e., precipitation – evaporation)
  - Use of in-situ leaching
  - Site-wide water flows in gallons per minute

HRM Financial Responsibility Formula: Examples of Expected Formula Reductions

- EPA is looking at **current** engineering controls as the basis for reductions to the baseline amount
  - Controls may already be present because of other regulatory programs, or undertaken voluntarily.
  - This approach will both reduce the amount of financial responsibility where strong regulatory controls are already present, and also provide an incentive for sound mining practices that will reduce financial responsibility costs for owners and operators.
- EPA intends to allow reductions from the baseline amount for controls such as those which result in reductions in volume, toxicity, and mobility of hazardous substances.
- Categories of reductions may include:
  - Feature-specific source control capital cost reductions
  - Site-wide drainage capital cost reductions
  - Capital and O&M reductions for water treatment
  - Short- and long-term O&M and monitoring reductions

Financial Responsibility Instruments

- EPA anticipates consideration of at least the following financial responsibility instruments:
  - Letter of Credit
  - Insurance
  - Trust Fund
  - Surety bond
  - Credit rating-based financial test/ corporate guarantee

Financial Responsibility Instruments (cont.)

- EPA has met with representatives of the insurance, surety, and banking communities who are experienced in providing instruments for other financial responsibility programs.
- Because the CERCLA 108(b) rule differs in operation from other existing programs, aspects of how the instruments would operate are novel.
- Novel criteria include the payout of the instrument under the direct action provision, the scope of coverage, and the payout to multiple claimants. Instrument providers will have to consider how to address these differences.
- EPA is considering the financial industry's feedback as it develops the instruments.

Potential Costs to Comply with the Rule

- EPA anticipates that the cost for a facility to comply with the proposed rule would largely stem from a limited number of requirements associated with the establishment and maintenance of the financial instrument, including:
  - Establishing a financial responsibility amount for the facility
  - Obtaining a financial responsibility instrument for that amount
  - Recordkeeping and reporting
- The cost to demonstrate evidence of financial responsibility will depend on site specific factors including: the financial responsibility level established for the facility; the choice of instrument; and other factors that instrument providers might consider.

Financial Responsibility Mine Example

- The following example highlights the key inputs used to develop FR amount and instrument pricing.

Commodity, Revenue, # employees	Site Features	Engineered Controls/ Best Practices	Best Practices Credit Reduction	FR Total ($millions)
▪ Gold ▪ $50-$100m ▪ <1,500 employees	• Open Pit ~200 ac • Waste Rock ~700 ac • Tailings Facility ~400 ac • 0"-25" Net Evaporation • Water Treatment Rate ~500 gpm	Open Pit Alkaline Amendments Waste Rock Segregation	~ 42%	~ $75

- The annualized cost of the instrument is driven primarily by the level of financial responsibility required, the parent company's financial characteristics (e.g., risk profile, cost of capital), and which instrument mechanism is used.

Annualized Instrument Costs to obtain $75 Million in FR ($millions)		
Instrument Type	Credit Rating	
	BBB-	CCC+
Insurance Policy	$4m	$19m
Trust Fund	$5m	$26m
Letter of Credit	$6m	$28m

Potential Costs to Comply with the Rule

Commodity, Revenue, # employees	Site Features	Engineered Controls/ Best Practices	Credit Reduction for Best Practices	FR Total ($millions)	Credit Rating/ Least Cost Instrument	Annualized Cost of Instrument ($million)
▪ Gold ▪ $50-$100m ▪ <1500 employees	• Open Pit ~200 ac • Waste Rock ~700 ac • Tailings Facility ~400 ac • 0”-25” Net Evaporation • Water Treatment Rate ~500 gpm	• Open Pit Alkaline Amendments • Waste Rock Segregation	~ 42%	~ $75	• BBB- • Insurance Policy covering known liabilities	~$4m
▪ Precious metals ▪ $50-$100m ▪ >1500 employees	• Underground Mine • Tailings Facility ~100 ac • 0”-25” Net Evaporation • Water Treatment Rate ~100 gpm	• Tailings Facility Alkaline Amendments • Paste or Filtered Tailings Deposition	~ 80%	~ $25	• B+ • Insurance Policy	~$1m
▪ Copper ▪ +$1000m ▪ >1500 employees	• Open Pit ~1000 ac • Waste Rock ~2000 ac • Tailings Facility ~700 ac • 75”-100” Net Evaporation • Water Treatment Rate ~1,000 gpm	• Wet Tailings Deposition	~ 24%	~ $525	• BB • Trust Fund	~$19m

Public Participation

- EPA is committed to ensuring transparency and to providing opportunities for public participation in its programs, including CERCLA.
- Public participation promotes greater awareness of the federal regulatory requirements.
- EPA understands that the public can play an important role in ensuring that the regulation achieves its goals.
- EPA is considering how to incorporate transparency and public participation into the HRM rule.

Process to Comply with the Rule

Initial Notification	Determine the Required Level of Financial Responsibility for the Facility	Obtain Financial Responsibility Instrument	Make Information Available	Maintain Financial Responsibility	Release from Financial ResponsibilityRequirements
• Following promulgation of the CERCLA 108(b) rule for hardrock mining, regulated facilities would be required to notify EPA, to provide basic information about the facility, and to obtain an EPA ID (if not previously issued to the facility).	• Facility owners or operators would be required to calculate the level of required financial responsibility by entering site-specific information about site features into the HRM financial responsibility formula. Facilities would be required to submit the calculated FR level, the formula inputs, and supporting information to EPA.	• Facilities would be required to obtain a financial responsibility instrument for the required level of financial responsibility, and to submit evidence of financial responsibility to EPA. • This requirement would be phased in, over a maximum period of four years after promulgation of the rule.	• The facility would be required to maintain information about the facility and the financial responsibility requirement, and to make that information available to the public.	• The owner and operator would be required to maintain evidence of financial responsibility throughout the facility life, update the level of financial responsibility as necessary but at least every three years, and notify EPA of certain changed conditions.	• At the end of the facility life, the owner or operator could apply for release of, or adjustment of, the level of financial responsibility. EPA would evaluate the facility and the need for continued financial responsibility, and would adjust the level of financial responsibility required, or release the owner or operator from the requirement to obtain financial responsibility.

Relationship of Section 108(b) Financial Responsibility to State, Tribal, and Local Government Law

- EPA's current view is that evidence of financial responsibility under Section 108(b) was not intended to preempt state or local mining reclamation and closure requirements.
- In particular, Section 108(b) financial responsibility is designed to assure that funds are available to pay for CERCLA liabilities, whereas EPA's review of state law financial responsibility requirements to date indicates that many are designed to assure compliance with state regulatory requirements and thus are not "in connection with liability for the release of a hazardous substance" under CERCLA Section 114(d).
- Similarly, EPA's current view is that evidence of financial responsibility under section 108(b) was not intended to preempt financial responsibility requirements that are designed to assure compliance with tribal mining reclamation and closure requirements.
- EPA plans to address this issue in the preamble of the proposed rule.

Relationship of Section 108(b) Financial Responsibility to Other Federal Law

- EPA has evaluated the applicability of Section 108(b) requirements at facilities where other federal financial responsibility requirements apply.
- EPA believes that Section 108(b) requirements, established to address CERCLA liabilities, are distinct from federal closure and reclamation bonding requirements imposed under other statutes.
- It is important to note that EPA intends the Section 108(b) financial responsibility amount to account for environmentally protective practices already in place, including those required by other regulations.

Market Study

- EPA is conducting a study to assess the capacity of third party markets to underwrite financial responsibility instruments required by the 108(b) rulemaking.
- The draft study examines both the current state and future outlook of the markets for financial responsibility instruments based on publically available and attributable data (from the US Treasury, GAO, Standard & Poor’s, industry, and non-profit institutions).
- The draft study report is currently undergoing internal review. EPA expects to make the report available before it issues the proposed hard rock mining rule.

Outreach Activities

- The next several slides describe specific outreach activities EPA will undertake in the coming months, concurrent with development of the proposed rule.
- EPA will perform any additional public outreach through the EPA's Superfund financial responsibility website.
- https://www.epa.gov/superfund/superfund-financial-responsibility

Federalism Consultation

- Pursuant to Executive Order 13132, "Federalism," EPA will consult with state and local government officials.
- The Order requires that Federal agencies consult with elected state and local government officials, or their representative national organizations, when developing regulations that have *Federalism Implications*.
- EPA is aware that representatives of the states have expressed concerns regarding CERCLA's express preemption provision in section 114(d). Therefore, the Agency is holding this consultation as part of ongoing efforts to involve its intergovernmental partners in the development of this proposed rule.
- The consultation provides the opportunity to discuss the approach to the proposed rule and hear concerns from state and local government officials.

Tribal Consultation

- EPA will consult with the federally recognized Indian tribes.
- Each tribe will be notified in writing of our CERCLA Section 108(b) rulemaking and will have the opportunity to request government-to-government consultation.
- Our goal is to ensure that tribal officials have sufficient information to be able to provide informed input on this rulemaking to EPA.
- EPA has already identified tribes that have their own financial responsibility requirements for hardrock mining. If more tribes have such requirements, we are interested in that information.

SBREFA

- The Regulatory Flexibility Act, as amended by the Small Business Regulatory Enforcement Fairness Act (SBREFA), requires EPA to convene a Small Business Advocacy Review (SBAR) Panel, consisting of representatives from three federal agencies, for proposed rules that will have a significant economic impact on a substantial number of small entities.
- Small entities are small businesses, small governments, and small organizations including appropriate trade associations. Small entity representatives have the opportunity to offer individual advice and recommendations to the SBAR Panel to ensure that we carefully consider small entity concerns.
- The SBREFA process for the CERCLA Section 108(b) rulemaking has already begun. We expect it to conclude with a SBAR Panel report listing recommendations to EPA.

How/When to Comment on the Proposed Rule

- The “CERCLA 108(b) Financial Responsibility Requirements for Facilities in the Hard Rock Mining Industry; Proposed Rule”, is due to be signed by December 1, 2016.
- The Proposed Rule will be published in the *Federal Register* and available for public review.
- The proposed rule will provide instruction on how to comment and the duration of the public comment period.
- We will consider public comments received during the comment period and EPA will provide responses at the time a Final Rule is issued.

Thank you!