Physical and Hydrologic Properties of Taconite Tailings

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1. Executive Summary

The Minnesota Department of Natural Resources (DNR) Lands and Minerals Division collected tailings cores of known provenance from four taconite operations during the summers of 2014 and 2015 as part of a larger study looking at sulfate generation, transport, and fate in taconite tailings basins on the Iron Range. Currently, little information exists on the hydraulic characteristics of taconite tailings, therefore, one goal of the present study was to increase the library of knowledge related to taconite tailings hydrology. Another goal was to generate hydrologic inputs that could be used in tailings basin water and sulfate balance models (Berndt et al. 2016). The major findings of the study were:

1) Fluvial deposition processes caused extensive particle size sorting in the tailings cells resulting in the largest tailings particles being deposited near the tailings discharge points in the cells and the smallest being deposited closer to the cell outlets.
2) Coarse tailings moisture contents were low and generally were homogeneous across all operations. Fine tailings core moisture contents were negatively correlated with tailings particle size. As a result, the fine tailings cores collected nearest to the tailings discharge points generally had the lowest moisture content and those collected near the tailings cell outlets had the highest moisture content.
3) Pore water Cl concentrations were elevated in most coarse and fine tailings cores that were only a few years in age and in the cores collected at the Hibtac tailings basin, indicating they still contained some of the process water that was initially entrained in the tailings at deposition. In contrast, pore water Cl levels generally were low in the older fine tailings cores indicating the process water once entrained in them had drained out and had been replaced by precipitation.
4) The tailings cores collected from the East Area Cell at Hibtac and the new fine tailings cores collected at the other operations likely were not free draining. A water table located deeper in the tailings potentially was controlling the rate at which those cores were dewatering.
5) A transient seepage model estimated the average yearly evaporation from a freely drained, Minntac fine tailings core to be 47 percent of total annual precipitation or approximately 10.5 inches. Net infiltration was estimated to be 12.0 inches.

2. Introduction

Understanding tailings dewatering rates and Infiltration rates are important parts of water balance and chemical loading studies, particularly in taconite tailings basins. Here we compile data on tailings physical properties, unsaturated water content, and pore water geochemistry and use the data to describe the spatial distribution of tailings particle sizes and water contents in taconite tailings basins. The data is also used to infer information about rates of tailings dewatering in tailings cores spanning a wide range of ages and particle size gradations. Lastly, the data is used to calibrate a transient water flow model that that is used to estimate the average annual infiltration rate for a fine tailings core. Ultimately, the modeling data will be used in tailings basin water balance models to predict the how much precipitation is seeping into the tailings in the basins.

3. Sampling Locations

A pick-up truck mounted Giddings Soil Probe (Giddings Machine Company, Windsor, CO) and 3.5-inch diameter soil coring tubes lined with PETG plastic liners were used to collect tailings samples of different ages at four taconite tailings basins during the summers of 2014 and 2015.

3.1. Hibtac

On July 14, 2015, tailings samples ranging in age from approximately 1 month to 9 years old were collected at eight locations in Hibbing Taconite's tailings basin (Figure 1). The basin is located north of the city of Hibbing, Minnesota in the Mississippi and Rainy River Watersheds.

Figure 1. Tailings sampling locations at the Hibtac tailings basin.

Six cores were collected on a north-south trending transect in the East Area Cell of the basin (Cores 1-6 in Figure 1) down to depths ranging from 40 to 90 inches, respectively. The southern part of the transect was located near the main tailings discharge to the East Area tailings cell and the northern part was located near the northern edge of the cell. The transect location was chosen to try and account for fluvial deposition processes that cause particle size sorting and layering during tailings deposition. Larger tailings particles are typically deposited near to the main discharge point and finer particles typically settle out further down gradient from the discharge location.

Tailings were last deposited in the East Area Cell between 2006 and 2009 and were unsegregated owing to the fact that Hibtac did not segregate their tailings into coarse and fine fractions when the tailings were originally deposited. Extensive reclamation had been conducted in the cell prior to core collection with the addition of biosolids and other amendments to the tailings surface and the planting of vegetation. Most of the cell generally was well covered with grasses ranging in height from a couple of feet to several feet tall.

A coarse tailings core was also collected down to a depth of 50 inches on the north facing slope of West Area 3 Cell dike. The section of the dike that the sample was collected from was recently raised in June, 2015 (Core 7 in Figure 1). Lastly, a fresh fine tailings sample was collected from a small beach area in the southwest corner of the West Area 1 Cell (Core 8 in Figure 1). Only a grab sample was collected at that location because the tailings were not solid enough to support the truck with the Giddings Probe.

3.2. Minntac

In 2014 and 2015, 15 fine and coarse tailings samples were collected from the Minntac tailings basin (Figure 2) ranging in age from brand new to approximately 29 years old. The basin is located near the City of Mt. Iron, Minnesota in the Rainy River Watershed.

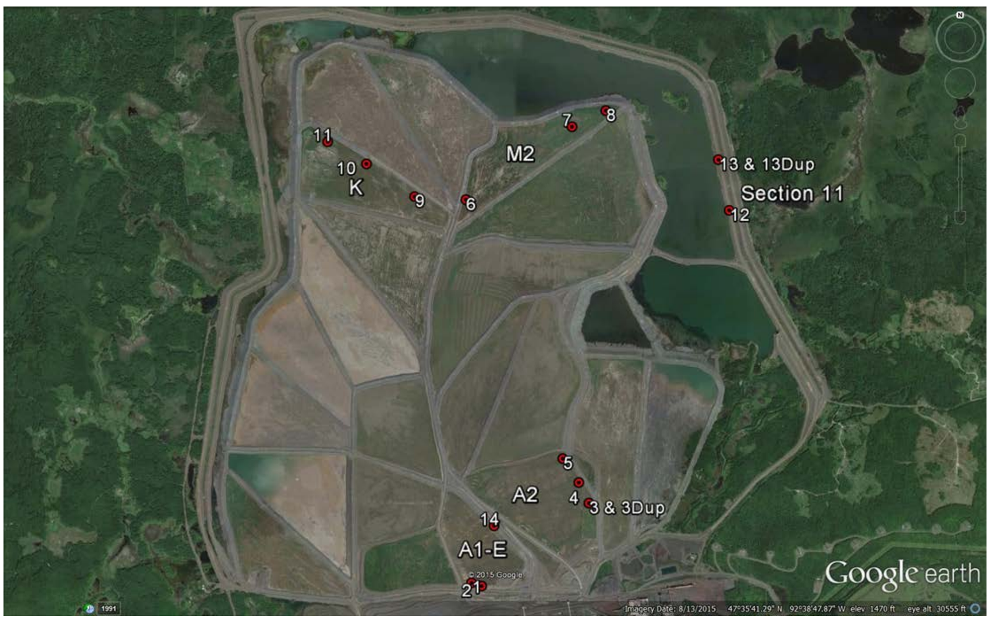

Figure 2. **Coarse and fine tailings sampling locations at the Minntac tailings basin.**

On September 17, 2014, two fine tailings cores were collected from Cell A1-E in the southern part of the tailings basin (Cores 1 and 2 in Figure 2) down to depths of 74 and 99 inches, respectively. Tailings had last been deposited in the cell in 1986 and the cell was covered with patchy vegetation including tall grasses and small trees and bushes.

Three fine tailings cores were also collected from Cell M2 in September, 2014 along a transect extending from the southwest corner of the cell near the cell inlet to the northeast corner of the cell near where tailings water is decanted into Cell 2 (Cores 6-8 in Figure 2). Tailings were last deposited in the cell in 2013 and reclamation conducted prior to sampling had covered the cell with a patchy layer of medium to tall grasses. There also was an extensive network of shrinkage cracks covering the tailings surface. Core sections were only collected down to a maximum depth of 24.5 inches in Cell M2.

In addition to the fine tailings cores, two coarse tailings cores were also collected from the Minntac basin in 2014. One of the coarse tailings cores was collected from Section 11 of the outer dike on the east side of the basin, which was raised between 1985 and 1990 (Core 12 in Figure 2). Core sections were collected down to a depth of 78 inches, respectively. A 2-inch diameter soil coring tube was used in conjunction with the 3.5-inch diameter tube to collect the coarse tails core sections due to problems getting through the coarse tailings with the larger diameter tube. A fresh, coarse tailings core was also collected from a section of the inner coarse tailings dike located between cells A1-E and A2 down to a depth of 34 inches, respectively (Core 14 in Figure 2). That section of the inner dike had recently been raised in 2014.

On June 6, 2015, nine more coarse and fine tailings cores were collected from the Minntac tailings basin. During the second round of core collection, three fine tailings cores were collected from Cell A2 which is located near Cell A1-E (Cores 3-5 in Figure 2). Tailings were last deposited in Cell A2 in 1986 and the tailings surface was covered with a patchy layer of tall grasses and small trees and bushes. Cores were collected along a transect extending from the southern part of the cell to the northern dike. All cores were collected on the east side of the cell near the coarse tailings dike because the small trees prevented access to much of the cell area. Core sections were collected in Cell A2 down to depths of 80 to 144 inches, respectively.

Three fine tailings cores were also collected along a transect extending from the east side of Cell K near the tailings discharge point to the west side where the tailings water is decanted into Cell 2 (Cores 9-11 in Figure 2). Like Cell M2, tailings had last been deposited in Cell K in 2012 and reclamation work had covered the cell with a patchy layer of medium to tall grasses. The tailings surface was also covered with an extensive network of shrinkage cracks. Core sections were collected in the cell down to depths of 26 to 59 inches, respectively.

Lastly, two coarse tailings cores were collected from Section 11 of the outer coarse tailings dike in 2015, just north of where core 12 was collected in 2014 (Cores 13 and 13Dup in Figure 2). Core sections were collected down to depths of 83 and 80 inches, respectively. A grab sample of freshly produced coarse tailings was also collected from within the plant in 2015.

3.3. Utac

On July 16, 2015, eight coarse and fine tailings cores ranging in age from approximately 7 months to 15 years old were collected at the United Taconite tailings basin (Figure 3). The basin is located in Forbes, Minnesota in the St. Louis River Watershed. Three fine tailings cores were collected from Basin 1 along a transect extending from the coarse tailings dike on the north side of the basin towards the center of the basin where a small wetland is now located (Cores 1-3 in Figure 3). Fine tailings core sections were collected down to depths of 83 to 89 inches, respectively in Basin 1.

The transect location was chosen to try and account for tailings particle size heterogeneity in the basin. During operation, the fine tailings were discharged into the basin near the outer edge of the dike and the tailings slurry flowed to a decant pond in the center of the basin. The discharge location was regularly rotated around the perimeter of the basin to keep the water pool in the center from encroaching on the outer dike. As a result, a beach area would have formed around the periphery of the basin near the discharge points containing a higher proportion of large, fine tailings particles. A zone containing very small tailings particles would have formed near the center of the basin where the clear water pool was located and a zone containing a mix of tailings particles sizes would have formed in between the beach and basin center.

After Basin 1 was closed, the DNR Lands and Minerals Division conducted several studies at the basin examining the viability of using biosolids and other organic substrates to improve vegetation establishment on taconite tailings (Eger et al., 2000; Eger and Antonson, 2005; Minnesota DNR Lands and Minerals, 2002). During a 2002 study, biosoilds were surface applied to most of the area where the fine tailings cores were collected. Utac's 2014 annual operating report indicates the Western Lake Superior Sanitary District (WLSSD) also applied biosolids to approximately 252.97 acres on Basin 1 in 2014 and biosolids will continue to be used on the basin in 2015. Currently, most of the fine tailings area in Basin 1 is covered with alfalfa, with the exception of the wetland and a small area with test plots covered by trees.

Three coarse tailings cores were also collected from the top crest of the coarse tailings dike on the north side of Basin 1 (Cores 5-7 in Figure 3). The tailings had undergone regrading and reclamation since closure and had also been amended with biosolids around 2000-2002. They were covered with patchy grasses that were a few feet in height. The coarse tailings core sections were collected down to depths of approximately 68 to 79 inches, respectively.

Lastly, one fine and one coarse tailings core were collected from Basin 2, which is the active tailings basin at Utac. The fine tailings core (Core 4 in Figure 3) was collected from a small beach area on the east side of the basin that last had active tailings deposition in January, 2015. Core sections were only collected down to a depth of 48 inches at that location. The coarse tailings core was collected from the crest of the Basin 2 dike near the beach area where the fine tailings core was collected (Core 8 in Figure 3). The dike at that location was last raised in June, 2014.

Figure 3. Coarse and fine tailings sampling locations at the Utac tailings basin.

3.4. ArcelorMittal

On July 23rd, 2015, seven fine and coarse tailings samples ranging in age from approximately 1 month to 15 years old were collected from ArcelorMittal's Upland Tailings Basin and Minorca In-pit Basin (Figure 4). Six of the cores were collected from the Upland Tailings Basin which is located northeast of the city of Virginia, Minnesota in the Rainy River Watershed. The seventh core was collected from the Minorca In-pit Tailings Basin which is located east of the city of Virginia in the St. Louis River Watershed.

Figure 4. Coarse and fine tailings coring locations at the ArcelorMittal Upland Tailings Basin (top panel) and Minorca In-Pit Basin (bottom panel).

In the Upland Tailings Basin, three fine tailings cores were collected along a north/south trending transect on the west side of Cell 2A (Cores 1-3 in Figure 4) down to depths of 62 to 90 inches, respectively. Tailings were last deposited into the cell between 2000 and 2001 and the cell had been reclaimed since closure. At the time of sampling, the cell was covered with small bushes and trees and patchy grasses that were a few feet in height.

Three coarse tailings cores were also collected from the northern crest of the Cell 2A dike (Core 5-7 in Figure 4). The section of the dike had last been raised between 1999 and 2000. Core sections were collected down to depths of 62 to 90 inches, respectively.

A new coarse tailings core was collected from a recently raised section of dike on the eastern edge Cell 2 in the Upland Basin (Core 8 in Figure 4). The dike was raised in June, 2014. Core sections were collected down to a depth of 41 inches at that location.

Lastly, a new fine tailings core was collected from the northeast corner of Minorca In-Pit Tailings Basin near the basin edge (Core 4 in Figure 4). The Minorca Basin was chosen for sampling because the tailings in the active tailings cell in the Upland Basin (Cell 2) were too soft to support the truck with the Giddings Probe. The Minorca In-Pit Basin was last active in 2014; however, it still receives short term, episodic discharges when pumping to the Upland Basin is down. Core sections were only collected down to a depth of 40 inches in the In-Pit Basin. The tailings surface in the basin was completely devoid of vegetation and contained a network of shrinkage cracks.

4. Methods and Procedures

4.1. Core Processing

4.1.1. Field

After collection, the ends of the plastic core liners were sealed with plastic caps and were wrapped with duct tape and the tailings grab samples were stored in sealed, plastic buckets. The individual core lengths were measured and any unique core features were logged prior to storing the cores for transport. The drill hole depth was also measured after each core section was collected and the change in drill hole depth was compared to the recovery lengths and total distance drilled in order to determine whether any tailings had sluffed back into the hole or whether the recovery length was less than the distance drilled. The data was then used to calculate the final depth interval over which each core was collected. After core collection was completed, the cores were taken back to the DNR laboratory in Hibbing, Minnesota for future processing.

4.1.2. Lab

At the lab, each core was weighed to the nearest gram and the core length was measured prior to removing the tailings from the plastic liners. After the weights and lengths were recorded, each core was extruded into a plastic trough for further processing. The top 2 inches of tailings, or any tailings that were noticeably different in color or texture, were discarded from the top of the core to remove any material that that may sluffed back into the hole after the previous core was collected. All large root masses were also removed from the core. However, some cores, such as the fine tailings cores collected from Utac Basin 1 that had alfalfa growing on them, had a significant amount of fine root mass in the upper core subsections that could not be completely removed. Observations of tailings color, wetness, density, and texture, were also made and any differences in core stratigraphy were noted. If there were significant stratigraphic differences in a core, the core was split along the boundaries between the different layers. All cores were then split in half lengthwise with a Plexiglas divider and the halves were placed into separate Ziplock bags, weighed, and labeled. One split was stored in the refrigerator for further on-site analyses and the other was sent to Lerch Brothers Inc. in Hibbing, Minnesota for analysis.

The core splits stored in the refrigerator were first homogenized prior to subsampling for other analyses. A 40 to 80 g sample was removed from each split, transferred into a 60 mL glass vial, and was then stored in the freezer for later microscopic analysis. A 50 g sample was also removed from each split for gravimetric moisture analysis. The moist samples were placed in 70 mm aluminum weighing dishes, weighed, and then dried at 110 °C for 24 hr. The samples were then reweighed after the 24 hr period and the change in weight was used to determine the amount of water that evaporated from the samples. A water density of 1.0 g cm^{-1} was used to compute the volume of moisture that was lost from each sample. Moisture content measurements were done in duplicate and averaged.

Tailings specific gravity was calculated for a select set of tailings samples using standard method ASTM D 854-92 for determination of specific gravity of solids. To determine the density of the solids, a 100 g tailings sample was first dried at 110 °C for 24 hr. The tailings were then placed in a 500 mL volumetric flask with deionized water and the volume of water in the flask displaced by the tailings was determined. Once the analyses were complete, the tailings samples were stored under refrigeration to maintain their integrity for possible future use.

Pore water was extracted from selected cores using a centrifuge (Thermo Scientific Sorvall Model ST8 Centrifuge) and 50 mL centrifuge tubes equipped with 25 mL cellulose acetate (0.45µm) maxi spin centrifuge filters. Centrifugation was used to remove the pore water because the tailings were not completely saturated and a positive pressure had to be applied to tails to remove the water that was tightly held in the particle matrix. Approximately 30 to 50 g tailings samples were centrifuged for a total of 15 min at 4500 RPM yielding water volumes ranging between 0.2 to 0.5 mL per tube for the coarse tailings and 2.5 to 5.0 mL for the fine tailings. The top foot or so of each coarse tails core was usually very dry and no pore water was able to be extracted from those subsections. The collected pore water samples were then pipetted into glass vials for storage. Often, fine dust would pass around the centrifuge filter and the samples had to be refiltered using a syringe filter with a 0.45 µm nylon membrane filter prior to storage. Pore water pH was also determined for a select set of samples pore water samples using an Orion 720A+ meter equipped with a Ross combination pH electrode (8165).

4.2. Tailings Particle Size Determination

Tailings particle size distributions were determined for selected core subsections by Lerch Brothers of Hibbing, Minnesota. Prior to sieving, Lerch Brothers split and homogenized the tailings samples using standard methods. After homogenization, the particle size distributions for the fine and coarse tailings samples were determined using 100 g tailings samples and wet and dry sieve methods. All coarse tailings samples were dry sieved into six size fractions using ASTM # 10, 40, 70, 140, and 200 sieves. In 2014, the fine tailings samples collected at Minntac were wet sieved into five size fractions using ASTM # 70, 200, 270, and 500 sieves. In 2015, all fine tailings samples were wet sieved into six size fractions using ASTM # 40, 70, 200, 270, and 500 sieves.

4.3. Major Cation and Anion Analysis

All tailings pore water samples were analyzed for major anions and a select set were analyzed for major cations at the University of Minnesota Analytical Geochemistry Lab, Minneapolis, Minnesota. Due to their small sample volume, some of the samples had to be diluted significantly to get enough sample for analysis. Cations were analyzed on a Thermo Scientific iCAP 6500 duo optical emission spectrometer (serial no. 20083410) fitted with a simultaneous charge induction detector. The system has separate slit openings for the low wavelengths < 232 nm and for those greater. All elements were measured on the most appropriate wavelength that is determined by the estimated composition, need for sensitivity, and the avoidance of element spectral overlaps. For each sample, standard, and blank the data is replicated five times to determine a mean and standard deviation for each selected elemental wavelength. Calibration is accomplished by comparing a NIST traceable single or multi-element standard solution to the unknowns. All blanks, standards, and samples are acid matrix matched to lessen matrix effects and are diluted such that element concentrations are in the linear working range of the standard and detector combination.

Anions were analyzed on a Dionex ICS-2000 ion chromatography system consisting of an AS11 analytical column, AMMS III suppressor, AS40 autosampler, and integrated dual piston pump and conductivity detector. The eluent is generated by Dionex's patented Reagent Free eluent generator system, which produces a variable concentration KOH eluent depending upon the request of the computer based software.

4.4. Water Isotopes

Pore water isotope samples were at analyzed at the University of Waterloo of Waterloo, Ontario, Canada using standard isotope ratio mass spectrometry methods. $^{18}O/^{16}O$ ratios were determined via gas equilibration and head space injection into an IsoPrime Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS). $^{2}H/^{1}H$ ratios were determined using chromium reduction on a EuroVector Elemental Analyzer coupled with an IsoPrime CF-IRMS. Internal laboratory standards are calibrated and tested against international standards from the International Atomic Energy Agency (IAEA), including Standard Light Antarctic Precipitation (SLAP), Greenland Ice Sheet Precipitation (GISP), and Vienna Standard Mean Ocean Water (VSMOW) $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ are reported in ‰ relative to the international standard Vienna Standard Mean Ocean Water (VSMOW), which approximates the composition of the global ocean. Sample replicates are run approximately every 8 samples. Analytical uncertainties are ±0.2‰ and ±0.8‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively.

Monthly water isotope ratios for local precipitation were estimated using the University of Utah IsoMAP isotopes in precipitation calculator online program http://wateriso.utah.edu/waterisotopes/index.html. The data sources used to construct the calculator can be found at: http://wateriso.utah.edu/waterisotopes/pages/data_access/oipc_citation.html.

4.5. Transient Water Flow Modeling

Transient water flow in the Minntac fine tailings was modeled using HYDRUS-1D, an open source finite element model for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media http://www.pc-progress.com/en/Default.aspx?hydrus-1d. The program numerically solves the Richards' equation for saturated-unsaturated water flow and Fickian-based advection dispersion equations for heat and solute transport.

Tailings hydraulic properties were determined using the measured particles size gradations and bulk density measurements, and the Rosetta DLL (Dynamically Linked Library) that is coupled with HYDRUS-1D (Schaap et al., 2001). Rosetta was developed by Marcel Schaap at the U.S. Salinity Laboratory and implements pedotransfer functions (PTFs) that predict van Genuchten (1980) water retention parameters and the saturated hydraulic conductivity (Ks) in a hierarchical manner from soil textural class information, the soil textural distribution, bulk density and one or two water retention points as input.

4.5.1. Climate Data

Climate input parameters in HYDRUS-1D were taken from a Minnesota Department of Natural Resources weather station located at the Hibbing-Chisholm Airport that is part of the MesoWest weather observation network. The weather station records can be found online at: http://raws.wrh.noaa.gov/cgiin/roman/meso_base.cgi?stn=HIBM5&unit=0&hours=6&day1=2&month1=8&year1=115&hour1=9&windred=25&time=LOCAL. Small gaps in the climate data record were filled for some variables using data from a NOAA weather station located at the main Chisholm-Hibbing Airport http://www.ncdc.noaa.gov/qclcd/QCLCD. The NOAA weather station did not measure all of the parameters that the DNR weather station measured. As a result, small data gaps for parameters not measured by the NOAA weather station had to be filled either using linear interpolation between values adjacent to the data gap or any large gaps in the data record were left blank. Climate records obtained from the weather station for 2010 to 2015 can be viewed in Appendix B.

5. Results

5.1. Core Physical Properties and Water Content

5.1.1. Hibtac Tailings Particle Size

The tailings cores collected near the tailings discharge location in the East Area Cell of the Hibtac tailings basin generally contained tailings particles that were sand size in texture (Cores 1 and 2 in Figure 5). Down gradient from the discharge point, the tailings particles became progressively smaller in size. Core 3 contained approximately 60 percent sand sized particles and 40 percent silt-clay sized particles, as compared to Cores 1 and 2 which contained mostly sand sized particles. From the middle of the cell to the northern edge (Cores 4, 5, and 6 in Figure 5); the tailings particles generally fell in the silt-clay size range. Tailings particles in the grab sample collected from a small beach area in the West Area 1 Cell also fell in silt-clay size range. In contrast, the coarse tailings core (Core 8) contained a significant proportion of gravel sized particles (≈ 20 percent) with the other 80 percent of the particles falling in the sand size range.

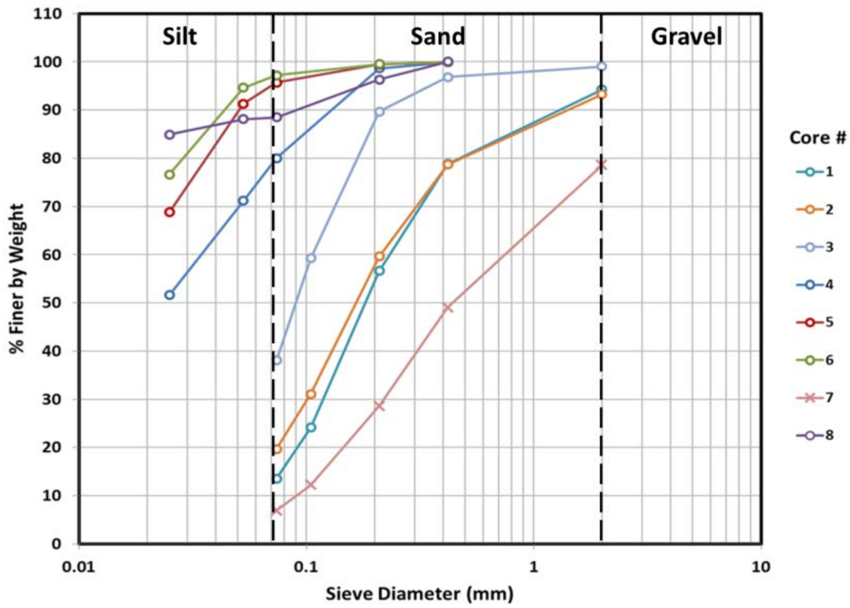

Figure 5. Average particle size gradations for tailings cores collected from the Hibtac tailings basin. Tailings particle sizes are classified using the USDA Soil Textural Classification System.

5.1.2. Hibtac Tailings Density and Water Content

Average bulk density values for the cores collected from the East Area Cell ranged from 1.38 to 1.51 g cm^{-1}, respectively (Table 1). Core bulk densities were highest on the south edge of the cell and decreased towards the northern edge. The coarse tailings core (Core 7) was denser than the cores collected in the East Area Cell with an average bulk density of 1.62 g cm^{-1}.

Average volumetric water contents for the cores collected from the East Area Cell ranged from 0.10 to 0.46 cm^3 cm^{-3}, respectively, and the unsaturated water to rock ratios ranged from 0.10 to 0.46 L water per kg tailings. Core volumetric water contents generally increased along the sampling transect with the core collected nearest to the cell inlet having the lowest moisture content and the core collected closest to the northern edge of the cell having the highest water content. The degree of core saturation also generally increased along the transect with the cores progressively becoming more saturated from the south section of the transect to the north. Average core saturation values ranged from 20 percent for Core 1 to close to saturation (88 percent) for Core 6. In contrast, the coarse tailings core was well drained and had a low moisture content. The average volumetric moisture content for the core was 0.07 cm^3 cm^{-3} or approximately 16 percent saturation with an unsaturated water to rock ratio of 0.04 L water per kg tailings.

Average pore water Cl concentrations were elevated in all of the cores collected from East Area Cell with respect to the average amount of Cl that is in precipitation in the region. The average weighted Cl concentration in precipitation at the USDA Forest Service research site in Marcell, Minnesota in 2014 was 0.041 mg L^{-1}. All precipitation chemistry data from the site can be found at: http://nadp.sws.uiuc.edu/data/sites/sitedetails.aspx?id=MN16&net=NTN. In contrast, average pore water Cl values for the cores collected in the East Area Cell ranged from 23.7 to 172.3 mg L^{-1}, respectively. These values bracketed the average Cl concentration for the fine tailings slurry of 55.0 mg L^{-1} (n = 5) measured in 2014 and 2015. The average pore water Cl concentration in the coarse tailings core (41.1 mg L^{-1}) also was elevated with respect to the Cl concentration in precipitation and was similar to that in the fine tailings slurry.

	Un-Segregated Tailings						Coarse Tailings
	East Area						West 3 Area
	1	*2*	*3*	*4*	*5*	*6*	*7*
Date of Last Deposition	2006 - 2009	2006 - 2009	2006 - 2009	2006 - 2009	2006 - 2009	2006 - 2009	6/2015
Sample Date	7/14/2015	7/14/2015	7/14/2015	7/14/2015	7/14/2015	7/14/2015	7/14/2015
Core Length (in)	88	81	65	65	43	64	50
Bulk Density (g cm^{-3})	1.48	1.51	1.37	1.46	1.35	1.36	1.62
Volumetric Moisture (cm^3 cm^{-3})	0.10	0.23	0.34	0.40	0.39	0.46	0.07
Saturation (%)	20	50	65	82	75	88	16
Unsaturated Water to Rock Ratio (L kg^{-1})	0.07	0.16	0.25	0.27	0.29	0.34	0.04
Saturated Water to Rock Ratio (L kg^{-1})	0.33	0.32	0.38	0.34	0.40	0.39	0.27
Pore Water Cl (mg L^{-1})	23.7	49.3	80.8	172.3	87.3	50.7	41.1
# of core sub-sections	7	8	6	5	3	6	3
# of pore water samples	5	7	6	5	3	5	2

Table 1. Average core physical properties and pore water Cl concentrations for the Hibtac cores. The values used to compute the averages were weighted by core subsection length. The number of core subsections and pore water samples used to calculate the averages are reported at the bottom of the table. The values used to compute the averages can be found in Table A 1 in Appendix A.

5.1.3. Minntac Tailings Particle Size

Unlike the tailings collected from the East Area Cell at Hibtac, Minntac tailings are segregated into coarse and fine fractions before being deposited in the tailings basin. As a result, the Minntac fine tailings cores, on average, contained a higher percentage of silt-clay sized particles compared to the cores collected at Hibtac because much of the large size fraction was separated into the coarse tailings (Figure 6). Even though the largest particle size fraction is removed from the Minntac fine tailings during processing, the particle size gradations for the fine tailings cores were still very heterogeneous with particle size being dependent on the proximity of the core to the tailings discharge point, and the pond that would have been located at the low end of the tailings cell during filling.

Fine tailings cores collected near the cell discharge point generally contained 40 to 55 percent silt-clay size particles and approximately 45 to 60 percent sand sized particles (Cores 1, 2, and 9 in Figure 6). In contrast, the tailings cores collected near to where the pond would have been located in the cell when it was being filled contained very little sand and upwards of approximately 90 percent silt-clay sized particles (Cores 7, 8, and 11 in Figure 6). Those cores likely contained a high percentage of clay sized particles because swelling of the tailings surface was observed during drilling. The particle size gradations for the cores that were collected between the discharge point and where the tailings pond was located contained anywhere from 20 to 45 percent sand size tailings particles and 55 to 80 percent silt-clay sized particles. In contrast, the particle size gradations for the coarse tailings cores (Cores 12–14 in Figure 6) and for the coarse tailings grab sample were very homogeneous with 20–50 percent of the particles in the tailings samples falling in the gravel size range and the rest falling in the sand size fraction.

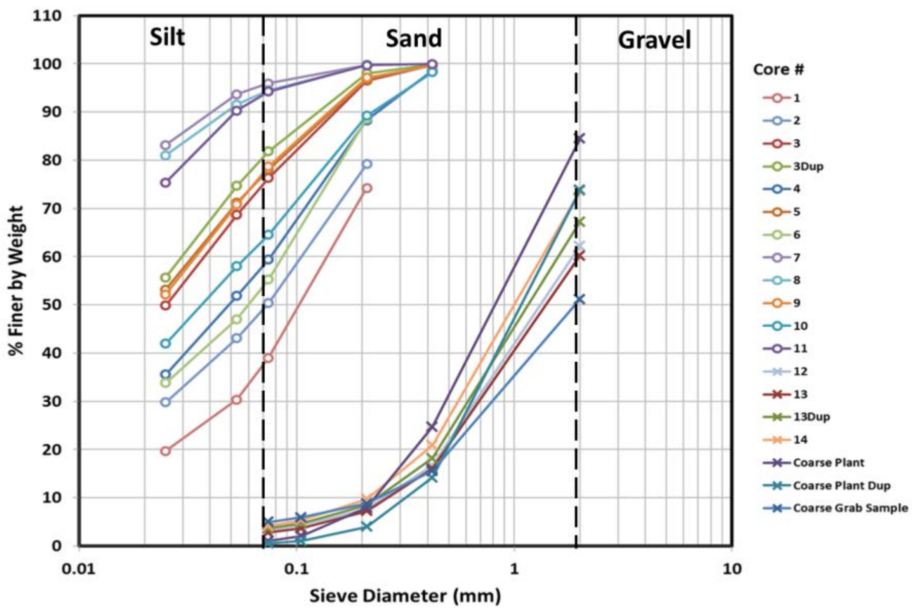

Figure 6. Average particle size gradations for tailings cores collected from the Minntac tailings basin. Tailings particle sizes are classified using the USDA Soil Textural Classification System.

5.1.4. Minntac Tailings Density and Water Content

Average bulk density values for the Minntac fine tailings cores were similar to the bulk density values for the Hibtac cores collected in the East Area Cell, ranging from 1.12 to 1.49 g cm^{-3}, respectively. Bulk density values for the coarse tailings cores were higher than the fine tailings bulk densities ranging between 1.62 and 1.79 g cm^{-3}, respectively. The values are comparable to the average bulk densities determined by Minntac for compact dry fine tailings (1.45 g cm^{-3}) and coarse tailings (1.75 g cm^{-3}). The average specific gravity of four Minntac coarse tailings samples was 3.00 g cm^{-3}.

Average fine tailings core volumetric moisture contents ranged from 0.16 to 0.44 g cm^{-3}, respectively, with unsaturated water to rock ratios ranging from 0.12 to 0.45 L water per kg tailings. In contrast, the average moisture contents for the coarse tailings cores ranged between 0.05 and 0.06 g cm^{-3}, respectively, with unsaturated water to rock ratios ranging from 0.03 to 0.04 L water per kg tailings. Average saturation values for the fine tailings cores ranged from 17 to 90 percent, whereas the coarse tailings cores were only at 11 to 16 percent saturation. Similar to Hibtac, the fine tailings cores collected nearest to the tailings discharge point generally had the lowest moisture contents and the cores collected near to where the pond was located in the cell when it was being filled had the highest moisture contents. Core saturation values also typically were lowest near the tailings discharge location and were highest near the outer edge of the cell.

Pore water Cl concentrations generally were low in the fine tailings cores collected in cells A1-E and A2, which were closed in 1986 and 1989. Average pore water Cl concentrations ranged between 6.5 and 11.0 mg L^{-3} in the cores collected in the two cells, which is higher than the Cl concentration in precipitation, but is much lower than the average 2011–2015 Cl concentration in the fine tailings slurry (151.2 mg L^{-1}, n = 8). In contrast, average pore water Cl concentrations were high in the cores collected in cells M2 and K, ranging from 32.3 to 274.6 mg L^{-1}, respectively. Pore water Cl levels were also elevated in the old coarse tailings cores collected from Section 11 of the outer dike ranging between 30.6 and 41.2 mg L^{-1}, respectively. The pore water Cl concentration was also high in the new coarse tailings core collected in 2014, measuring 187.3 mg L^{-1}.

	Fine Tailings											Coarse Tailings			
	Cell A1-E		Cell A2				Cell M2			Cell K			Section 11			
	1	*2*	*3*	*3Dup*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*13Dup*	*14*
Date of Last Deposition	1986	1986	1989	1989	1989	1989	2013	2013	2013	2013	2013	2013	1985-1990	1985-1990	1985-1990	2014
Sample Date	9/17/14	9/17/14	6/17/15	6/17/15	6/17/15	6/17/15	9/17/14	9/17/14	9/17/14	6/17/15	6/17/15	6/17/15	9/17/14	6/17/15	6/17/15	9/17/14
Core Length (in)	74	99	93	144	87	80	22	24.5	15	59	36	47	78	83	80	34
Bulk Density (g cm^{-3})	1.29	1.46	1.26	1.27	1.35	1.36	1.25	1.38	1.12	1.38	1.47	1.48	1.73	1.65	1.79	1.62
Volumetric Moisture (cm^3 cm^{-3})	0.16	0.20	0.26	0.28	0.19	0.35	0.10	0.35	0.34	0.24	0.20	0.44	0.06	0.06	0.06	0.05
Saturation (%)	29	36	45	51	36	68	17	68	56	47	41	90	16	16	16	11
Unsaturated Water to Rock Ratio (L kg^{-1})	0.12	0.14	0.45	0.22	0.14	0.26	0.08	0.26	0.30	0.18	0.14	0.30	0.04	0.04	0.03	0.03
Saturated Water to Rock Ratio (L kg^{-1})	0.43	0.44	0.45	0.44	0.39	0.39	0.45	0.38	0.54	0.38	0.34	0.33	0.23	0.24	0.21	0.27
Pore Water Cl (mg L^{-1})	6.5	11.5	8.0	7.1	7.1	7.1	274.6	32.3	196.1	89.0	128.2	172.4	41.2	30.6	31.7	187.3
# of core sub-sections	8	11	7	10	5	7	4	3	3	3	2	3	7	6	5	3
# of pore water samples	8	6	7	10	5	7	1	2	2	3	4	3	6	4	4	2

Table 2. Average core physical properties and pore water Cl concentrations for the Minntac cores. The values used to compute the averages were weighted by core subsection length. The number of core subsections and pore water samples used to calculate the averages are reported at the bottom of the table. The values used to compute the averages can be found in Tables A 2 and A 3 in Appendix A.

5.1.5. Utac Tailings Particle Size

Like Minntac, Utac also separates their tailings into coarse and fine size fractions. Similar to the other operations, extensive particle size sorting occurs during fine tailings deposition (Figure 7). Cores 1 and 4, which were collected near the tailings discharge points in Basin 1 and Basin 2, contained 80 to 90 percent sand sized particles and only 10 to 20 percent silt-clay sized particles. In contrast, Core 3, which was collected near the center of the Basin 1 where the decant pond was located when the basin was active, contained approximately 5 percent sand and 95 percent silt-clay sized particles. Core 2, which was collected approximately half way between Cores 1 and 3 had a particle size gradation intermediate to the other two fine tailings cores collected in Basin 1, containing approximately 30 percent sand sized particles and 70 percent silt-clay sized particles. The coarse tailings cores collected from both Basin 1 and Basin 2 were relatively homogeneous in texture and contained anywhere between 20 and 45 percent gravel and 55 to 80 percent sand size particles, which were similar to the gradations for the Minntac coarse tailings cores.

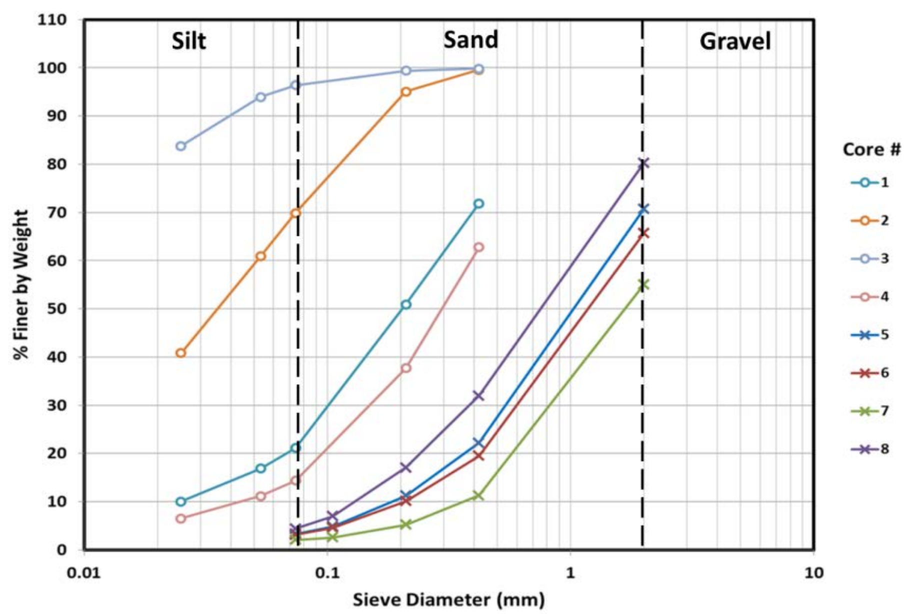

Figure 7. Average particle size gradations for tailings cores collected from the Utac tailings basin. The tailings particle sizes are classified using the USDA Soil Textural Classification System.

5.1.6. Utac tailings Density and Water Content

Average bulk density values ranged between 1.25 and 1.58 g cm^{-1} for the fine tailings cores collected from Basin 1 and Basin 2 at Utac (Table 3). Fine tailings density values were highest near the basin perimeter and progressively decreased toward the center of the basin. Average bulk density values for the coarse tailings were similar across cores ranging from 1.63 to 1.77 g cm^{-3}, respectively, which was similar to coarse tailings bulk density values at other operations.

Fine tailings volumetric moisture contents ranged from 0.07 to 0.25 cm^3 cm^{-3} and increased from the basin perimeter to the center of the basin. Unsaturated water to rock ratios ranged from 0.05 to 0.13 L water per kg tailings for the fine tailings cores. Fine tailings saturation values also exhibited a progressive increase from the edge of the basin to the center with saturation values increasing from 16 to 17 percent near the edge to 45 percent near the center of the basin. Volumetric moisture values were fairly constant across all coarse tailings cores ranging from 0.04 to 0.05 $cm^3\ cm^{-3}$ with saturation values ranging from 9 to 12 percent, respectively. Unsaturated water to rock ratios ranged from 0.02 to 0.03 L water per kg tailings for the coarse tailings cores.

Average pore water Cl values generally were low in the fine tailings cores collected from Basin 1. Cl levels ranged from 2.3 to 4.9 mg L^{-1}, respectively in Cores 2 and 3. In contrast, the average pore water Cl concentration in Core 1 was 17.5 mg L^{-1} which was elevated compared to other fine tailings cores collected in Basin 1 but was lower than the average for the fine tailings slurry in 2014–2015 (58.3 mg L^{-1}, n = 4). The pore water Cl concentration in the fine tailings core collected from Basin 2 was 96.3 mg L^{-1} which was almost double the average Cl concentration in the fine tailings slurry, but was only about 20 mg L^{-1} higher than the Cl concentration in the fine tailings slurry in February, 2015, which was approximately when the tailings were deposited in Basin 1. Similar to the coarse tailings cores at the other operations, Cl levels were elevated in the coarse tailings cores collected in Basin 1 ranging from 20.6 to 27.0 mg L^{-1}, respectively. Surprisingly, the average pore water Cl concentration for the newer coarse tailings core collected in Basin 2 (8.9 mg L^{-1})was lower than the average pore water Cl concentrations for the older coarse tailings cores.

	Fine Tailings				**Coarse Tailings**			
	Basin 1			**Basin 2**	**Basin 1**			**Basin 2**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Date of Last Deposition	05/2000	05/2000	05/2000	01/2015	08/1999	08/1999	08/1999	06/2014
Sample Date	7/16/2015	7/16/2015	7/16/2015	7/16/2015	7/16/2015	7/16/2015	7/16/2015	7/16/2015
Core Length (in)	83	89	85	48	79	74	68	48
Bulk Density (g cm^{-3})	1.53	1.32	1.25	1.58	1.70	1.72	1.77	1.63
Volumetric Moisture ($cm^3\ cm^{-3}$)	0.07	0.18	0.25	0.08	0.04	0.05	0.04	0.04
Saturation (%)	16	33	45	17	10	12	10	9
Unsaturated Water to Rock Ratio (L kg^{-1})	0.05	0.13	0.20	0.05	0.02	0.03	0.02	0.02
Saturated Water to Rock Ratio (L kg^{-1})	0.31	0.41	0.45	0.29	0.24	0.24	0.22	0.27
Pore Water Cl (mg L^{-1})	17.5	4.9	2.3	96.3	27.0	20.6	24.5	8.9
# of core sub-sections	7	6	7	3	7	7	7	3
# of pore water samples	4	4	4	2	3	3	2	2

Table 3. Average core physical properties and pore water Cl concentrations for the Utac cores. The values used to compute the averages were weighted by core subsection length. The number of core subsections and pore water samples used to calculate the averages are reported at the bottom of the table. The values used to compute the averages can be found in Tables A 4 and A 5 in Appendix A.

5.1.7. ArcelorMittal Tailings Particle Size

Similar to the other operations, average tailings particle sizes in the ArcelorMittal's Upland Tailings Basin generally were largest near the tailings discharge point in the tailings cell and were smallest near where the process water pond would have been located when the cell was active (Figure 8). Core 1, which was located nearest to the discharge point in Cell A2, contained approximately 45 percent sand and 55 percent silt-clay sized particles. In contrast, the core collected nearest to the end of Cell A2 (Core 3 in Figure 8) contained about 5 percent sand and upwards of 95 percent silt-clay sized particles. The particle size gradation for Core 2, which was collected in between Cores 1 and 3, fell intermediate to the two cores containing approximately 20 percent sand and 80 percent silt-clay size particles. The fine tailings core that was collected from the Minorca In-Pit Basin (Core 4) was coarser in texture than the other fine tailings cores containing approximately 50 percent sand and 50 percent silt-clay size particles. The particle size gradations for the coarse tailings cores (Cores 5–8 in Figure 8) were very similar to the coarse tailings cores collected at the other operations containing about 20 percent gravel and 80 percent sand sized particles.

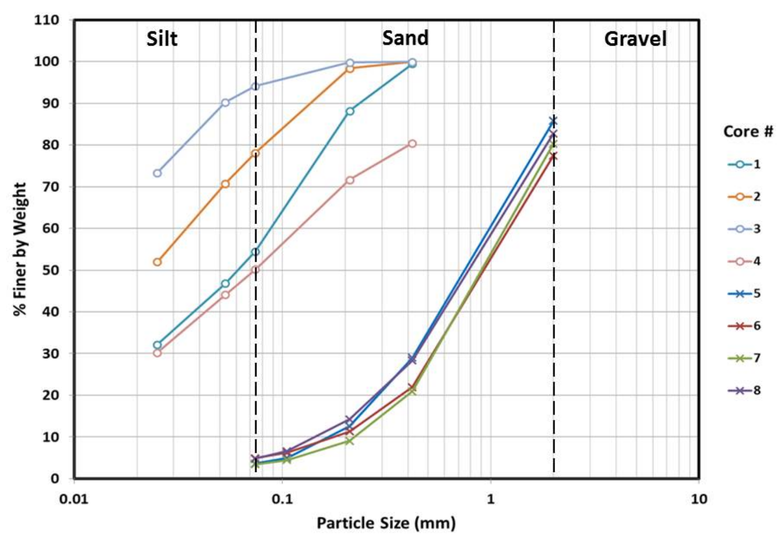

Figure 8. Average particle size gradations for the cores collected from the ArcelorMittal Upland and Minorca In-Pit tailings basins. The Tailings particle sizes are classified using the USDA Soil Textural Classification System.

5.1.8. ArcelorMittal Tailings Density and Water Content

Bulk density values for fine tailings cores collected in Cell 2A ranged from 1.26 to 1.36 g cm^{-1}, respectively (Table 4). In contrast, the average bulk density for the core that was collected in the Minorca In-Pit Tailings Basin (Core 4) was 1.52 g cm^{-1}. Bulk density values for the coarse tailings cores were very similar to coarse tailings bulk densities at other operations ranging from 1.61 to 1.74 g cm^{-1}, respectively.

In Cell 2A, the fine tailings volumetric moisture values increased along the sampling transect with average core moisture contents ranging from 0.16 cm^3 cm^{-3} near the southern edge of cell to 0.36 cm^3 cm^{-3} near the northern edge with unsaturated water to rock ratios ranging from 0.10 to 0.27 L water per kg tailings. Core saturation values ranged from 33 to 67 percent, respectively. The volumetric moisture content of the core collected from the Minorca In-Pit Tailings Basin was 0.15 cm^3 cm^{-3} or about 32 percent saturation. Like at the other operations, the coarse tailings cores collected from the Upland Tailings Basin were well drained with volumetric water contents ranging between 0.04 and 0.05 cm^3 cm^{-3} and saturation values ranging between 10 and 12 percent, respectively. The unsaturated water to rock ratios for the coarse tailings cores ranged from 0.02 to 0.02 L water per kg tailings.

Pore water Cl levels were low in the fine tailings cores collected from Cell 2A ranging from 1.4 to 4.4 mg L^{-1}. In contrast, the average pore water Cl concentration in the core collected from the Minorca In-Pit Basin was 210 mg L^{-1}, which was a little more than double the average fine tailings slurry Cl concentration measured in 2014 and 2015 (94.5 mg L^{-1}, n = 5). Average coarse tailings core pore water Cl concentrations were also elevated, ranging between 16.0 and 145.8 mg L^{-1} for the coarse tailings cores collected from the Cell 2A dike and 42.1 mg L^{-1} for the new coarse tailings core collected from the Cell 2 dike.

	Fine Tailings				**Coarse Tailings**			
	Cell 2A			**In-Pit**	**Cell 2A**			**Cell 2**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Date of Last Deposition	2000-2001	2000-2001	2000-2001	2014	1999-2000	1999-2000	1999-2000	06/2014
Sample Date	7/23/2015	7/23/2015	7/23/2015	7/23/2015	7/23/2015	7/23/2015	7/23/2015	7/23/2015
Core Length (in)	80	62	90	40	78	62	90	41
Bulk Density (g cm^{-3})	1.26	1.36	1.30	1.52	1.61	1.74	1.69	1.67
Volumetric Mositure (cm^3 cm^{-3})	0.16	0.28	0.36	0.15	0.05	0.04	0.05	0.05
Saturation (%)	33	53	67	32	10	10	12	11
Unsaturated Water to Rock Ratio (L kg^{-1})	0.13	0.21	0.27	0.10	0.03	0.02	0.03	0.03
Saturated Water to Rock Ratio (L kg^{-1})	0.37	0.39	0.42	0.31	0.28	0.23	0.25	0.25
Pore Water Cl (mg L^{-1})	4.4	3.2	1.4	210.0	16.0	145.7	47.3	42.1
# of core sub-sections	7	7	6	3	7	7	7	3
# of pore water samples	4	4	4	2	4	4	4	2

Table 4. Average core physical properties and pore water Cl concentrations for ArcelorMittal cores. The values used to compute the averages were weighted by core subsection length. The number of core subsections and pore water samples used to calculate the averages are reported at the bottom of the table. The values used to compute the averages can be found in Tables A 6 and A 7 in Appendix A.

5.2. HYDRUS-1D Modeling

Precipitation records and climate variable records needed to estimate evaporation in HYDRUS-1D using the Penman Monteith Method were obtained from a weather station maintained by the Department of Natural Resources at the Hibbing-Chisholm Regional Airport near Hibbing, Minnesota. These variables included relative humidity, solar radiation, maximum temperature, minimum temperature, and average temperature and wind speed. Daily climate records were used as inputs in the model and the records can be viewed in Appendix B in Figures B 1–B 5. For brevity, only monthly averages for the different climate variables are reported in Table B 1 in Appendix B, however, the daily climate records can be obtained upon request or can be found at the station website. Climate records for the period of January, 2010 through August, 2015 are shown in the figures. However, only the records covering the period from May, 2012 through August, 2015 were used in the model due to discrepancies in the 2010 and 2011 relative humidity and solar radiation data.

Before HYDRUS-1D was used to model water flow through any tailings cores, the model was first calibrated using tailings pore water isotope measurements. Water isotopes were used to calibrate the model because factors such as seasonal changes in air masses that affect a region (Sjostrom and Welker, 2009) and changes in evapotranspiration rates cause the isotopic composition of precipitation to vary on a seasonal basis. As a result, pore water isotope measurements can be used to approximate pore water age if the isotope ratios are known for precipitation at different times of the year. The ages can then be used to estimate water flow using a piston type soil water flow model if the following is assumed: 1) all new precipitation that percolates deep into the tailings core displaces old precipitation downward in the tailings profile, 2) there is little mixing of different age pore waters in the profile allowing the water to remain isotopically distinct, and 3) the precipitation that percolates deep into the tailings profile is marginally impacted by evaporative processes that can cause the pore water to be more enriched with heavier isotopes compared to the original precipitation.

Pore water measurements from Minntac core 3Dup were used to calibrate the HYDRUS-1D model because pore water Cl concentrations were low in the core, indicating that all of the water in the core was sourced from precipitation and not from process water, and because complete pore water isotope records were not available for any other cores. The pore water isotope measurements from core 3Dup and the estimated monthly precipitation isotope ratios for the region can be seen in Figure 9. Based on the pore water isotope record, it was assumed that evaporation had negligible impact on the pore water isotope values because the pore water measurements plotted on a line with a slope similar to the global meteoric water line. Comparing the pore water isotope ratios to the estimated monthly values, it was estimated that the precipitation that had fallen on the core had percolated to a depth of approximately 94 inches over 1 year. This was because the pore water isotope ratios for the core subsections collected at a depth of 55 to 74 inches and 77 to 94 inches were most similar to the isotope ratios for the pore waters located near the surface of the core.

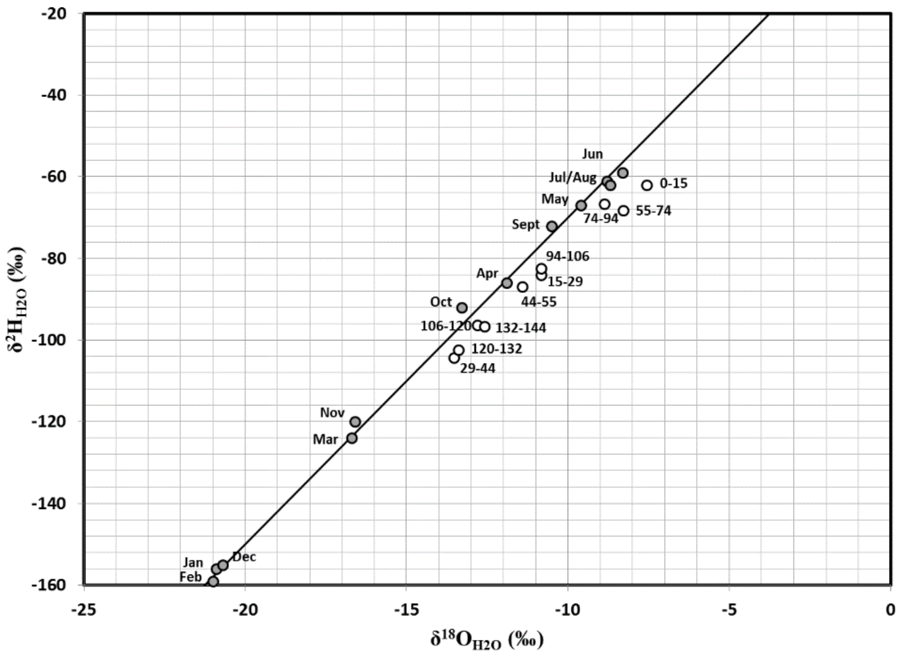

Figure 9. Estimated monthly $\delta^{18}O$ and δ^2H values for precipitation in Northeastern Minnesota (solid circles) and measured isotope ratios for Minntac core 3Dup porewaters (open circles). The number ranges next to the open circles indicate the depth intervals from which the pore water samples were extracted. The solid line represents the Global Meteoric Water Line (GMWL).

The hydraulic properties for core 3Dup were estimated using the Rosetta DLL in HYDRUS-1D and the measured bulk density and particle size distribution for the core. The Rosetta DLL uses percentage sand, silt, and clay size particles as one set of inputs to estimate hydraulic characteristics; however, no information was available on the percentage of clay size particles in the core. Therefore, it was assumed the core contained, on average, 25 percent sand sized particles, 75 percent silt sized, and 0 percent clay sized particles with an average bulk density of 1.27 g cm^{-1}. The fact that no clay sized particles were used to estimate the hydraulic properties of the tailings could have resulted in hydraulic conductivities being slightly over estimated for the core.

The pore water isotope measurements indicated a significant amount of water in the core was less than one year old because precipitation from the previous June was found at a depth of approximately 94 inches. As a result, water flow in the core was modeled over the time period from May 31st, 2014 to June, 30th 2015 to try and match the estimated pore water ages. The May 31st start date was chosen instead of June 1st because a very large precipitation event impacted the region from May 31st to June, 2st 2014. The Penman Monteith Method was used to estimate evaporation from the tailings core. It was assumed there was zero plant transpiration and zero runoff in the model, which were reasonable assumptions given the fact that vegetation only sparsely covered the cell where the core was collected, there was little to no root biomass in the core, and the slope of the tailings beach where the core was collected was very shallow, which would have limited runoff. The bottom boundary condition in the model was set to free drainage which would occur if there was no water table controlling the rate of water drainage from the core. The initial tailings temperature was set to 10 $^{\circ}$C in the model and the initial volumetric water content was adjusted so that there was no rapid change water storage or drainage at beginning of the model run that would have resulted from the tailings either being too dry or to wet to start with.

To estimate the pore water age at different depths in the core using HYDRUS-1D, an inert tracer (referred to as Cl) was added to the pore water near the surface of the core at the beginning of the model run. The tracer concentration in the pore water was set to 150 mg L^{-1}, which is approximately equal to the average Cl concentration in the Minntac tailings slurry. To make the simulation behave like a piston flow model, dispersion was set to a very low value so there was little mixing of the pore water containing the Cl with old water in the core or new precipitation. The depth of the Cl front was then tracked at monthly time steps over 1 year to estimate how much percolation occurred during each month (Figure 10). To estimate the water age at different depth intervals in the core, the depth of the Cl front at each monthly time step was subtracted from the depth of the front at the previous time step to determine how far the water had percolated during that time step.

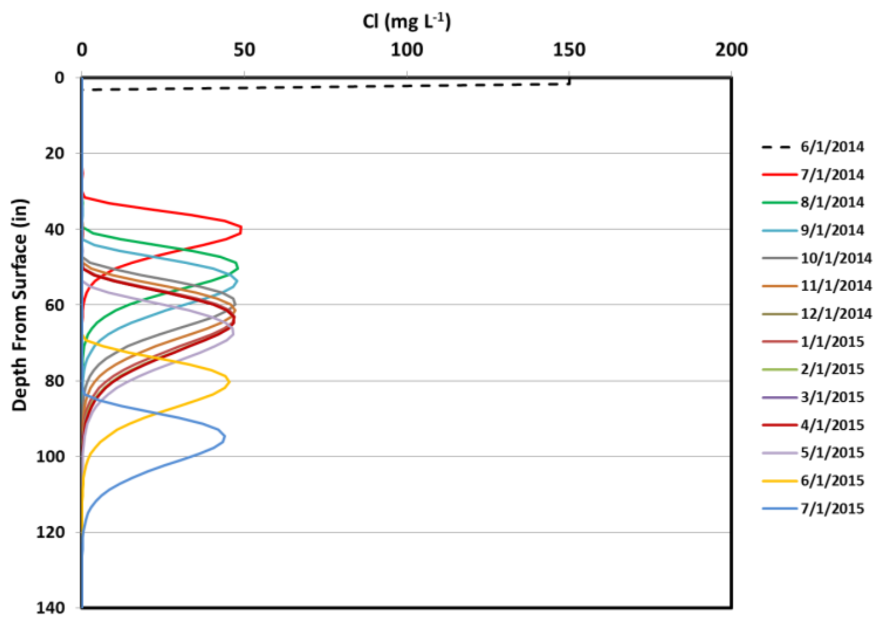

Figure 10. Monthly Cl front depths estimated by HYDRUS-1D for Minntac core 3Dup.

Those values were then used to construct an age profile assuming the precipitation that infiltrated into the core in June, 2015 was at the top of the core and the precipitation from June, 2014 was at the bottom (Figure 11). To get the estimated pore water isotope profile to approximately match the measured profile, the tailings albedo had to be adjusted to 0.45 in the model; or the modeled Cl front did not move deep enough into the profile during the one year model period. Sands can have albedo values close to 0.45; however, albedos for most soils typically are closer to 0.25.

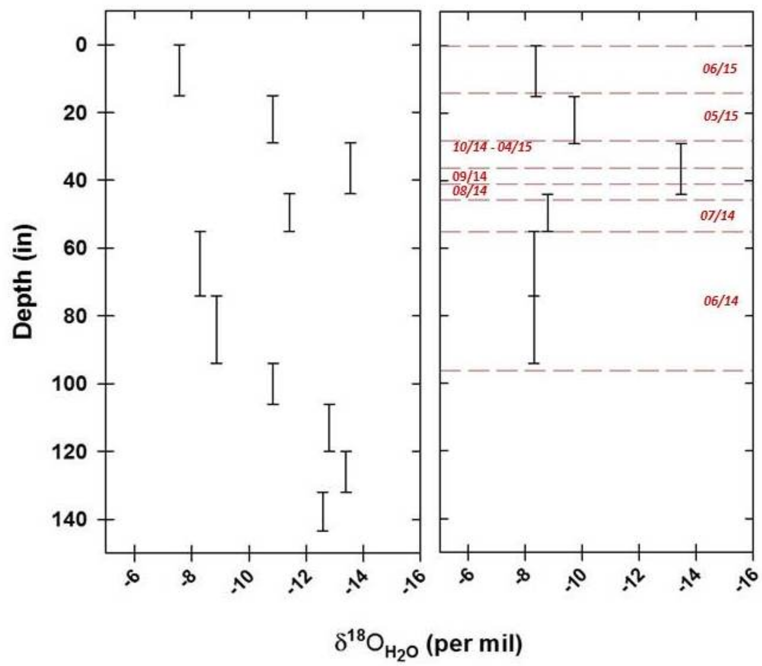

Figure 11. Measured pore water $\delta^{18}O$ profile in Minntac core 3Dup (left panel). The vertical lines in the figure indicate the depth intervals from which the pore water samples were extracted. The dashed lines in the right panel denote the estimated boundaries between different aged pore waters in the core and the dates indicate the pore water age estimated by HYDRUS-1D for that section of the core. The pore water isotope ratios in the right panel were estimated using the pore water age estimates and the average montly $\delta^{18}O$ values for preciptation in Northeastern Minnesota. Isotope values on the x-axis are reversed with larger values on the left side of the axis and smaller values on the right.

In general, the modeled pore water isotope values exhibited similar variation with depth as the measured values. However, there was some discrepancy between the estimated values and measured values. The modeled pore water isotope concentrations for the core subsections that were estimated to contain July, 2014 and May, 2015 precipitation were less negative than the measured values, indicating the bulk water in those cores was younger than was estimated. Winter-spring precipitation typically is isotopically lighter than precipitation that falls during the summer and early fall months. The slight mismatch between the estimated and measured values was likely due to the fact that water did not move purely by piston flow in core 3Dup. This resulted in some mixing of different age pore waters in the core, especially during periods when percolation rates were low.

The volumetric moisture contents estimated by HYDRUS-1D for core 3Dup were slightly lower than the average measured value of 0.28 $cm^3\ cm^{-3}$ (Figure 12). This was possibly due to the actual tailings texture being finer than what was estimated from the sieve size data. Also, an average particle size gradation was used to estimate the hydraulic properties for the core. In reality, particle size was not homogeneous with depth and it is possible tailings layer(s) with lower hydraulic conductivities were impeding water flow in the core and causing measured water contents to be slightly higher that they would be if particle sizes were homogeneous.

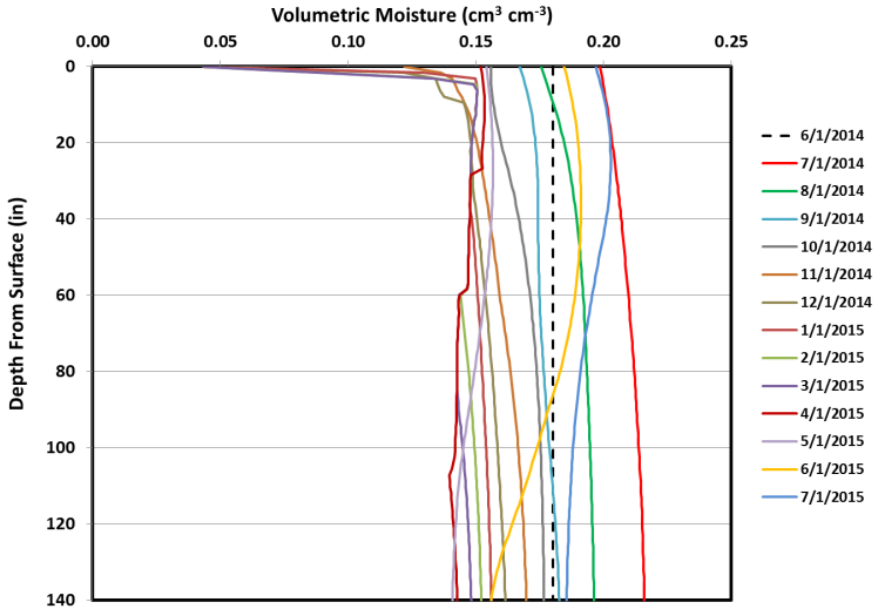

Figure 12. Monthly volumetric moisture contents estimated by HYDRUS-1D for Minntac core 3Dup.

Modeled tailings temperatures varied greatly over the one year period (Figure 13), with the greatest temperature variations occurring in approximately the top 80 cm of tailings. Surface soil temperatures typically track air temperature, so it is not surprising modeled surface temperatures varied greatly over the model run. In contrast, temperature variations were much more muted with depth and modeled temperatures were approximately twenty degrees cooler at the bottom of the core than at the surface in June, 2015. This is consistent with observations made in the field in which the core subsections collected from deeper in the profile were much cooler to the touch (even in mid-June) than the ones collected from nearer the surface.

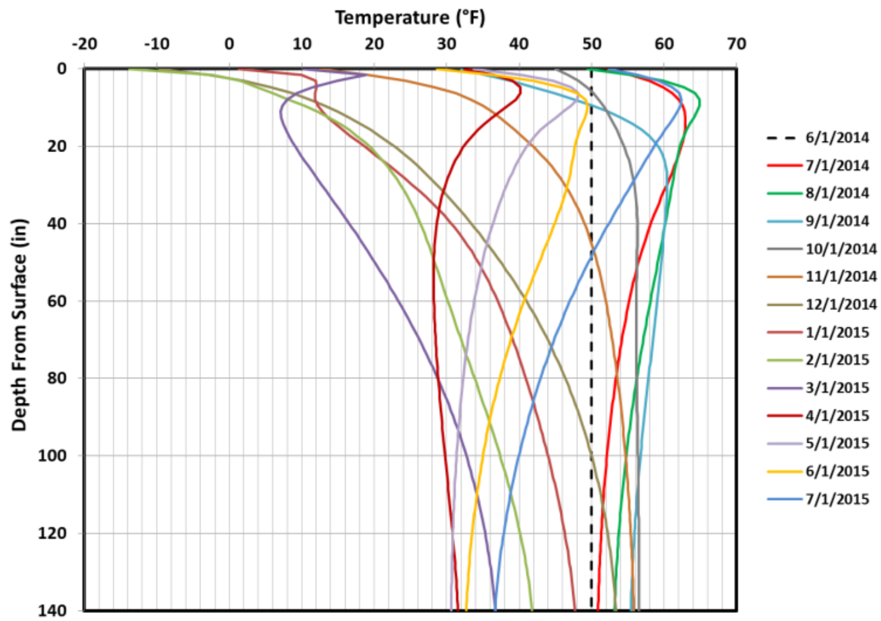

Figure 13. Monthly tailings temperatures estimated by HYDRUS-1D for Minntac core 3Dup.

Approximately 27 inches of precipitation was applied to the core during the model run (Figure 14). Total evaporation from the tailings surface was equal to approximately 28 percent of total precipitation over the same period. The estimated evaporation value is less than annual evaporation values for Northeast Minnesota watersheds, which typically are closer to 2/3 of total annual precipitation.

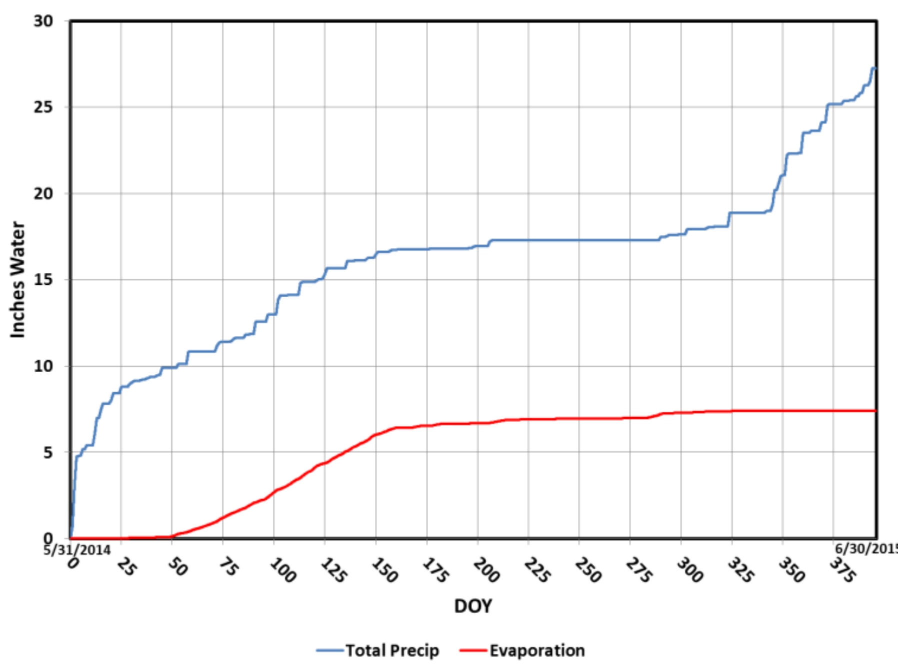

Figure 14. Cumulative precipitation applied to Minntac core 3Dup and cumulative evaporation estimated by HYDRUS-1D for the time period from 5/31/2014 to 6/30/2015.

Net infiltration for Minntac core 3Dup was approximately 20 inches from May 31, 2014 to June 30, 2015, which was equal to total precipitation minus evaporation for the period because there was no runoff (Figure 15). In the short term, there was significant storage of precipitation in the core following the large precipitation event in late May-June 2014 and during spring 2015. However, in the long term the total amount of drainage from the core was approximately equal to net infiltration, indicating water storage over the entire period was approximately zero.

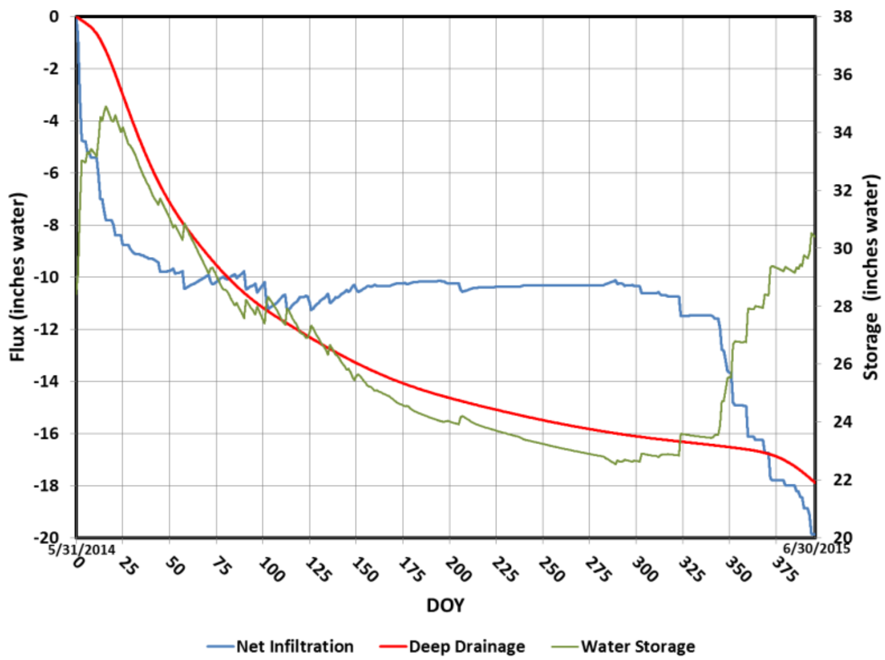

Figure 15. Cumulative infiltration, deep drainage, and water storage estimatd by HYDRUS-1D for Minntac core 3Dup for the time period from 5/31/2014 to 6/30/2015.

After the HYDRUS-1D model was calibrated to Minntac core 3Dup, it was used to model transient water flow in a core with a particle size gradation similar to the weighted average for all Minntac fine tailings cores. The particle size gradations for the very fine textured cores were not used to calculate the particle size average due to the limited amount of data on clay sized particles in those cores. An average particle size gradation of 55 percent sand and 45 percent silt and an average bulk density of 1.3 g cm^{-3} were ultimately used to estimate the hydraulic characteristics of the tailings using the Rosetta DLL in HYDRUS-1D. The start of the model run period was changed to May 1st, 2012. The end was changed to August 31, 2015 so that evaporation, infiltration, and drainage could be estimated over several years.

While the model run was started in 2012, only the results from 2013–2015 were used to estimate annual evaporation, infiltration, and drainage. The results from the first year of the model run were not used to compute yearly averages because the initial tailings moisture content and temperature may not have been representative of the actual water content and temperature on that date, and therefore could have affected the model results at the beginning of the simulation. Total precipitation from May 1st, 2013 to May 1st, 2014 and from May 1st, 2014 to May 1st, 2015 was estimated to be 22.3 and 22.6 inches, respectively (Figure 16, Table 5). Over those same periods, evaporation was equal to approximately 48 and 45 percent of total precipitation, which was higher than the percentage of precipitation evaporated in the calibration model run. The cumulative evaporation estimates were different between model runs because cumulative evaporation was 2 to 3 inches lower and total precipitation was 5 inches greater in the calibration model run compared to the longer model run.

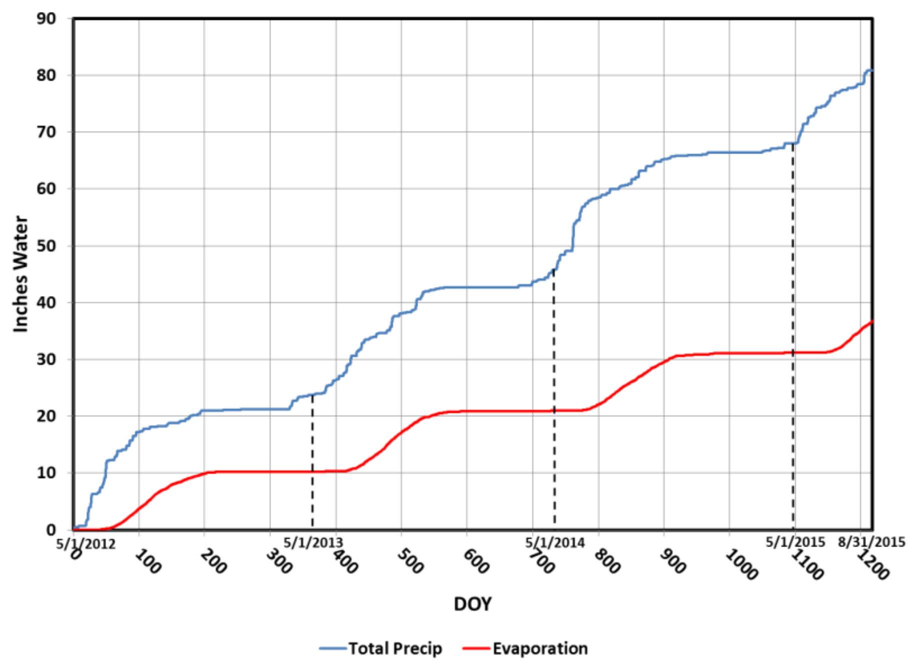

Figure 16. Cumulative precipitation applied to a tailings core with a particle size gradation similar to the average for all Minntac fine tailings cores and cumulative evaporation from the core estimated by HYDRUS-1D for the time period from 5/1/2012 to 8/31/2015.

HYDRUS-1D estimated deep drainage to be approximately 2.7 inches less than net infiltration for the period from May 1st, 2014 to May 1st, 2015 and about 2.2 inches more than net infiltration for the period from May 1st, 2014 to May 1st, 2015. This indicated over the two year period that storage was approximately zero, and therefore drainage could be assumed to generally be at quasi steady-state in the long term (Figure 17, Table 5).

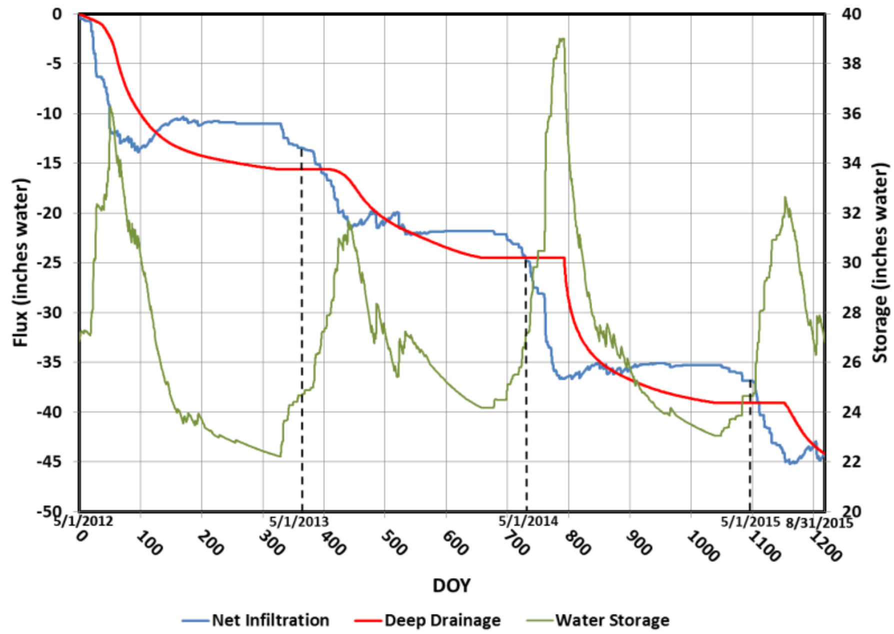

Figure 17. Cumulative infiltration, deep drainage, and water storag estimatd by HYDRUS-1D for a tailings core with a particle size gradation similar to the average for all Minntac fine tailings cores for the time period from 5/1/2012 to 8/31/2015.

	5/1/13 - 5/1/14	5/1/14 - 5/1/15
Total Precip (in)	22.3	22.6
Evaporation (in)	10.7	10.2
Net Infiltration (in)	11.6	12.4
Deep Drainage (in)	8.9	14.6
Net Storage (in)	2.7	-2.2

Table 5. Cumulative evaporation, infiltration, drainage,and stoage estimated by HYDRUS-1D for the time periods from 5/1/2012 to 5/1/2014 and 5/1/2014 to 5/1/2015.

6. Discussion

6.1. Tailings Physical Properties and Water Content

Overall, coarse tailings particle size distributions were very homogeneous, and gradations generally were similar across operations. In contrast, particle size gradations for the fine tailings cores were very heterogeneous at the individual operations, and also across operations. A major factor affecting the texture of the cores was the proximity of the core to the tailings discharge point and the pond that was located in the tailings cell when it was active. At all operations, fluvial processes resulted in a higher percentage of sand sized fine tailings particles being deposited near the discharge point in the tailings cells and more silt-clay sized particles being deposited closer to the pond.

Coarse tailings bulk density values were similar across all operations, ranging from approximately 1.60 to 1.80 g cm^{-3}, respectively. Bulk density values for the fine tailings cores spanned a wider range of values, ranging from approximately 1.25 to 1.60 g cm^{-3}, respectively, across all operations. Since bulk density partly is a function of particle size, core bulk density values generally were highest near the tailings discharge points in the tailings cells, and were lowest near where the pond was located in the tailings cell when it was active.

All coarse tailings cores were well drained with volumetric moisture contents ranging between 0.04 to 0.07 cm^3 cm^{-3} and saturation values ranging between approximately 10 to 16 percent, respectively. Even though the coarse tailings cores were well drained, pore water Cl concentrations were quite high in several of the newer coarse tailings cores, indicating precipitation still had not displaced all of the old process water that was deposited with the tailings when the dikes were raised. In some cases, elevated pore water Cl concentrations were measured up to a year after deposition.

Cl levels were also elevated in many older coarse tailings cores that had been deposited between 1985 and 2000. It is currently unknown where the Cl in those cores is sourced from. If the Cl is sourced from old process water, then a significant amount of the process water that was deposited with the tailings when the dikes were raised would be immobile and water and flow through the cores would be bypassing a percentage of the pore spaces in the tailings. The Cl in the cores could also be sourced from process water that is sprayed on the coarse tailings dikes as dust control.

At Utac, the Cl in the coarse tailings cores collected from Basin 1 could also be sourced from the biosolids that were applied to the coarse tailings dike in 2000. Research has shown, at least in the short term, that biosolids applied to coarse tailings can leach appreciable amounts of Cl, sulfate, and nitrate at rates dependent upon the initial biosolid application rate (Eger and Antonson, 2005; Eger et al., 2000). However, biosolids were also applied to the fine tailings in Basin 1 and Cl levels also should have been elevated in those cores if the biosolids were still leaching Cl which was not the case. Therefore, the dissolved Cl in the coarse tailings cores collected from Basin 1 likely was not sourced from biosolids.

In contrast to the coarse tailings, average fine tailings core water contents varied greatly across all basins ranging from 0.07 cm^3 cm^{-3} to 0.46 cm^3 cm^{-3}, with saturation values ranging from 16 percent to almost 100 percent. Fine tailings moisture contents were negatively correlated with tailings particle size across all basins, with the same general relationship between particle size and moisture content holding across all operations (Figure 18). The relationship between particle size and water content is not linear because soil water holding capacity does not increase linearly with decreasing pore size. Since volumetric water content is negatively correlated with tailings particle size, average fine tailings core volumetric water contents generally were lowest near the tailings discharge points where average particle sizes were the largest, and were highest near where the ponds were located in the tailings cells when they were active where particle sizes were the smallest.

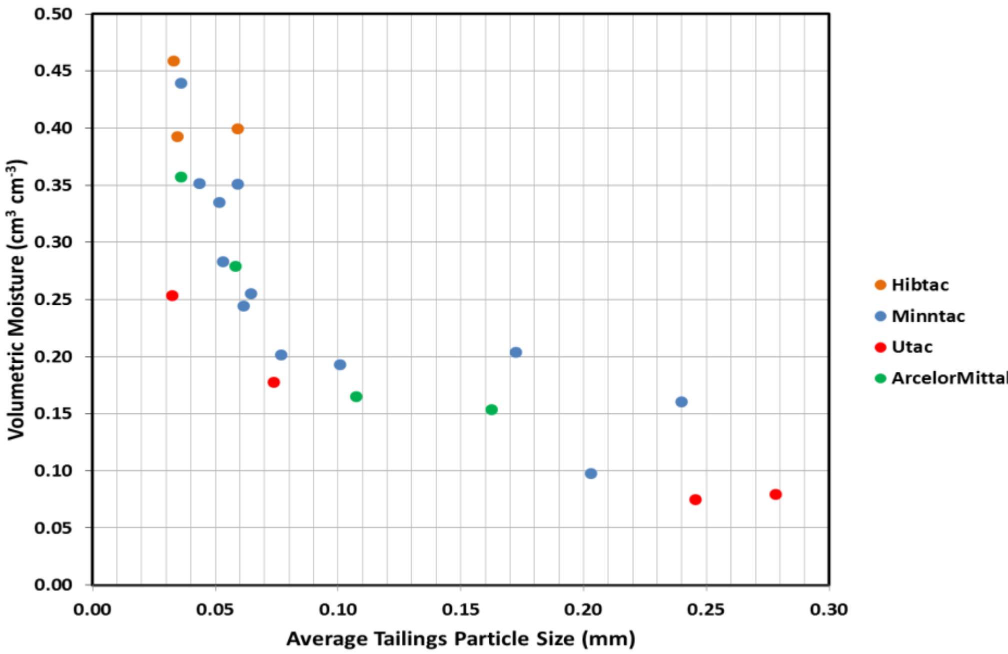

Figure 18. Relationship between fine tailings core particle size and volumetric water water content acossr all operations. The average particle sizes in the figure do not necessarily represent the actual average particle sizes for the cores because full particle size gradations were not measured.

With the exception of the unsegregated tailings cores collected at Hibtac and the "new" fine tailings cores collected from cells M2 and K at Minntac, and the Minorca In-Pit Basin, pore water Cl levels generally were low in the other fine tailings cores indicating the process water that was initially entrained in the tailings during deposition had drained out and had been replaced by precipitation.

In contrast, pore water Cl levels were elevated in all of the cores collected from the East Area Cell in the Hibtac tailings basin. Even though the cell was last active in 2009, the pore water in the cores still contained significant amounts of Cl possibly indicating the old process water that was initially entrained in the tailings had not fully drain out. However, Hibtac also applied biosoilds to the East Area Cell prior to sampling. Since biosolids have been shown to leach Cl, it is unknown whether all the Cl in the pore waters was sourced from the old process water entrained in the tailings during deposition or whether some was sourced from the biosolids applied to the tailings after cell closure.

While it is difficult estimate how much of the Cl in the Hibtac cores is sourced from old process water because of the biosolids addition to the East Area Cell tailings, pore water isotope measurements for the East Area Cell cores indicate a significant amount of process water is still entrained in many of the cores after almost six years because many of the pore water isotope values are similar to the water isotope ratios for the fine tailings slurry (Figure 19). The pore water isotope measurements also suggest that some old process water has drained out of a few of the cores because some pore water isotope values from Cores 1 and 6 plotted closer to the global meteoric water line than to the tailings slurry indicating process water entrained in the tailings had been mixed with new precipitation.

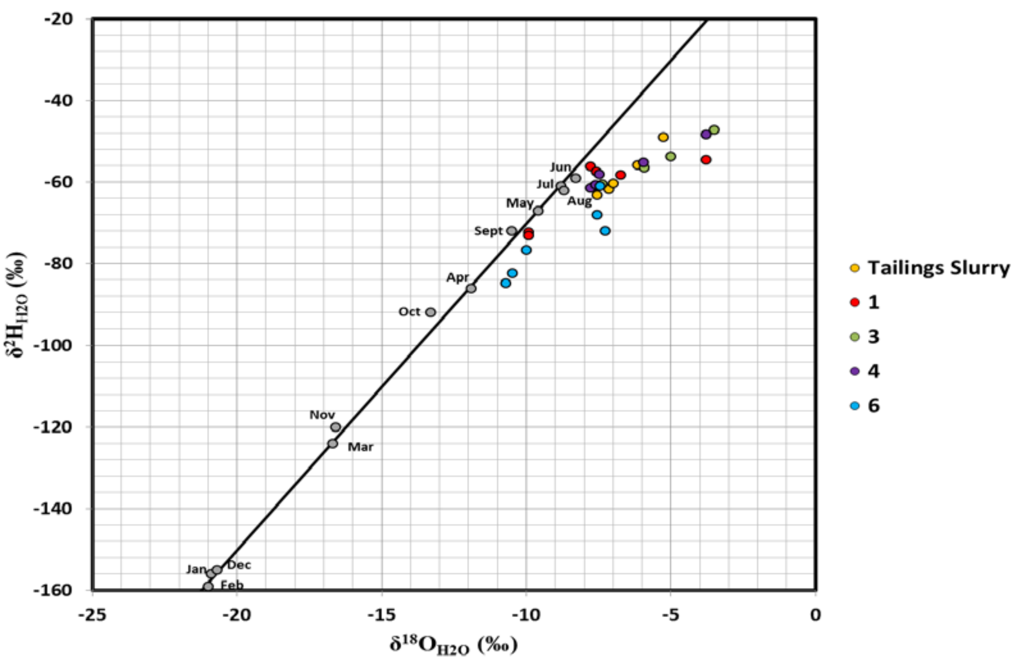

Figure 19. Pore water isotope ratios for tailings the cores collected from the East Area cell at Hibtac compared to water isotopes for the Hibtac fine tailings slurry and average isotope ratios for preciptation in the region.

The fine tailings cores collected from cells M2 and K at Minntac and the core collected from the Minorca In-Pit Tailings Basin at ArcelorMittal also had elevated pore water Cl levels approximately one to two years after deposition. No biosolids were applied to cells M2 and K; therefore, the Cl in the cores was most likely sourced from process water entrained in the tailings during deposition indicating all of process water initially entrained in them had not fully drained out. Core pore water Cl concentrations generally bracketed average 2014-2015 fine tailings slurry Cl concentrations for each operation indicating evaporation had concentrated the salts in some cores and newly infiltrated precipitation had diluted the Cl in others.

The coarse tailings cores as well as most of the fine tailings cores that are older than a few years in age could generally be considered to have a free drainage boundary at the bottom of them because a steady increase in saturation with depth was not seen in any of the cores, which would potentially indicate a water table located at some depth below the cores was controlling the rate of drainage from the them (Appendix A, Tables A1-A4). Also, the low pore water Cl levels in the older fine tailings cores indicates precipitation had displaced all of the old process that was initially entrained in the tailings pore spaces. In contrast, the younger fine tailings cores and the cores collected at Hibtac likely are not freely drained because all of the process water initially entrained in the cores had not been completely displaced by precipitation. Also because tailings moisture contents increased with depth in several cores, reaching near saturation in some, indicating a water table located at some depth below the cores in the tailings was likely controlling the rate of process water drain down from the cores.

6.2. HYDRUS-1D Modeling

The predicted evaporation from Minntac Core 3Dup (28 percent of total precipitation) was much lower than average annual evapotranspiration values for Northeast Minnesota watersheds, which are usually closer to 2/3 of annual precipitation. One major factor that drove down the total evaporation predicted by the model was the fact that HYDRUS-1D did not compute any appreciable evaporation from the tailings surface until mid-July. Spring and early summer evaporation rates had to be low in the model in order to displace the Cl front deep enough into the core to match the total percolation predicted by the pore water isotope profile. This, however, runs contrary to typical seasonal changes in potential evapotranspiration rates (the amount of evapotranspiration that would occur if sufficient water was available) for the region (Figure 20). Estimated evapotranspiration rates are predicted to start increasing in early spring and to peak around July and August. However, HYDRUS-1D predicted no evaporation from the tailings surface until July.

Several factors could explain the discrepancy between the estimated evapotranspiration rates and those predicted by HYDRUS-1D. First, plant transpiration was not included in the model because there was only sparse vegetation in the cell and little root mass in the core. The addition of plants to the model would have increased total evaporation rates during growing periods, which would have increased spring and early summer evaporation and also would have increased total evaporation. Second, actual soil evaporation can be much less than potential evaporation when the supply of water at the soil surface is low, therefore tailings moisture may have been limiting evaporation in the spring. However, modeled moisture contents were highest in June-July of both years, suggesting moisture availability likely was not limiting tailings evaporation in the model. Energy availability also could have limited spring evaporation. During the spring tailings temperatures in the model were increasing, indicating heat was being stored in the tailings, which would have limited the amount of energy available to evaporate water from the tailings and would have decreased total predicted evaporation.

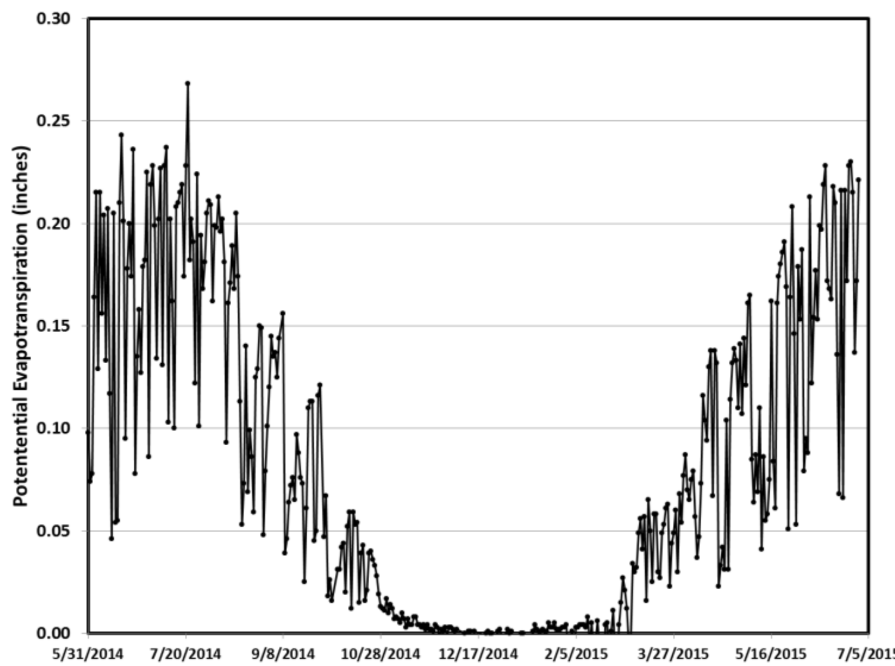

Figure 20. Potential evapotranspiration rates estimated for Northeastern Minnesota by the University of Wisconsin-Agricultural Weather Service using the Priestly-Taylor Equation and remote sensing measurements (Diak et al, 1998). The daily evapotranspiration estimates can be downloaded at (http://agwx.soils.wisc.edu/uwex_agwx/sun_water/et_wimn)

The total amount of annual evaporation predicted by HYDRUS-1D for the Minntac fine tailings was low compared to typical evaporation values. However, the average annual deep drainage predicted by the model (11.8 inches) was very similar to recharge estimates made for the tailings basin aquifer in the old National Steel Tailings Basin (now Keetac) located near Keewatin, Minnesota (Myette, 1991). In the study, recharge to the tailings basin aquifer was determined graphically using water level fluctuations measured in wells installed in the tailings and specific yield estimates for the tailings at each observation well. Overall, recharge was estimated be to be 11.8 inches for water year 1983 (October 1, 1982 to September 30, 1983) and 10.0 inches for calendar year 1983 which is very close to modeled drainage rates suggesting the modeled water flows were reasonable approximations of actual water flow in the unsaturated zone of the Minntac fine tailings.

7. Major Findings

1) Coarse tailings particle size gradations exhibited little variation between basins. In contrast, fine tailings core particle size gradations exhibited a high degree of spatial variation at each basin. The coarsest textured fine tailings cores were collected near the tailings discharge points and the finest were collected nearest to where the ponds would have been located in the cells when they were active.
2) Coarse tailings moisture contents were low for all cores, whereas fine tailings core saturation values ranged from approximately 10 to almost 100 percent across all basins. Average

volumetric moisture contents for the fine tailings cores were negatively correlated with tailings particle size. As a result, the fine tailings cores generally were least saturated near the tailings discharges and were most saturated near where the ponds would have been located in the tailings cells when they were active.

3) Pore water Cl levels were elevated in the old and new coarse tailings cores collected at all operations. The Cl in the new cores was likely sourced from the process water that was deposited with the tailings when the dikes were raised. The source of Cl in the older coarse tailings cores currently is unknown.
4) Pore water Cl concentrations generally were low in the older fine tailings cores, indicating that precipitation had replaced the process water initially entrained in them during deposition. In contrast, pore water Cl levels generally were elevated in the cores that were only a few years old and in the Hibtac cores, indicating process water was still entrained in those cores.
5) The cores collected from the East Area cell in the Hibtac basin and other fine tailings cores that were only a few years in age likely were not freely drained. A water table located at some depth below the cores was possibly controlling the rate at which they were dewatering.
6) Pore water stable isotope measurements combined with precipitation stable isotope measurements were shown to be a useful tool for determining pore water age. Pore water isotopes indicated precipitation had percolated to a depth of 94 inches in a fine tailings core collected in the Minntac tailings basin.
7) HYDRUS-1D estimated that annual evaporation from a fully unsaturated, fine tailings core with a particle size gradation similar to the average for all Minntac fine tailings cores was equal to 47 percent or of total annual precipitation, or 10.5 inches. Average net infiltration was estimated to be 12.0 inches.

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Appendix A.

Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^{3} cm^{-3})	Saturation (%)	$\delta^{18}O_{H2O}$ (‰)	δH^{2}_{H2O} (‰)	Pore Water Cl (mg L^{-1})	Wet Sieve Size Fraction (100 g start weight) (mm) +0.42	0.42 - 0.21	0.21 - 0.074	0.074 - 0.053	0.053 - 0.025	-0.025
4	East	2006-2009	7/14/2015	0.0	11.0	1.54	47	0.45	95	-6.0	-55.1	325.2	0.1	0.5	7.5	7.6	26.7	57.6
4	East	2006-2009	7/14/2015	11.0	21.0	1.23	57	0.26	46	-7.8	-61.4	154.1	0.0	0.1	49.7	16.9	23.6	9.7
4	East	2006-2009	7/14/2015	21.0	28.0								0.0	0.8	22.5	15.6	25.5	35.6
4	East	2006-2009	7/14/2015	28.0	44.0	1.58	46	0.41	91	-7.6	-60.7	133.5						
4	East	2006-2009	7/14/2015	44.0	55.3	1.45	50	0.47	93	-3.8	-48.3	139.7	0.0	2.5	9.0	3.6	11.5	73.4
4	East	2006-2009	7/14/2015	55.3	64.5	1.46	50	0.38	76	-7.5	-58.1	137.2	0.2	1.6	13.0	7.9	18.0	59.3
5	East	2006-2009	7/14/2015	0.0	20.0	1.23	57	0.32	55			112.8	0.1	0.3	5.0	8.2	36.4	50.0
5	East	2006-2009	7/14/2015	20.0	27.0	1.41	51	0.47	91			67.6	0.1	0.5	2.6	0.5	5.6	90.7
5	East	2006-2009	7/14/2015	27.0	36.0													
5	East	2006-2009	7/14/2015	36.0	43.3	1.50	48	0.47	97			57.2	0.1	0.7	2.5	0.9	12.2	83.6
6	East	2006-2009	7/14/2015	0.0	9.5	1.07	63	0.34	54	-10.0	-76.7	48.4	0.1	0.6	1.6	0.6	8.9	88.2
6	East	2006-2009	7/14/2015	9.5	23.0	1.18	59	0.50	84	-7.3	-72.0	39.8	0.0	0.9	2.8	0.2	2.7	93.4
6	East	2006-2009	7/14/2015	23.0	34.0	1.25	57	0.51	91	-10.5	-82.4							
6	East	2006-2009	7/14/2015	34.0	57.0	1.51	48	0.47	99	-10.7	-84.8	52.0	0.1	0.3	2.7	5.6	27.7	63.6
6	East	2006-2009	7/14/2015	57.0	64.0	1.43	51	0.38	74	-7.6	-67.9	56.5	0.0	0.4	3.5	5.6	35.3	55.2
6	East	2006-2009	7/14/2015	64.0	79.0	1.63	44	0.47	108	-7.5	-60.9	55.7	0.0	0.2	1.5	1.0	16.9	80.4
8	West 3	04-05/2015	7/14/2015	Grab								115.0	0.0	3.7	7.8	0.4	3.2	84.9

Table A 1. Hibtac core physical properties and moisture contents.

													Dry Sieve Size Fraction (100 g start weight) (mm)					
Core #	**Cell**	**Date of Last Depostion**	**Sample Date**	**Top Depth (in)**	**Bottom Depth (in)**	**Bulk Density (g cm^{-3})**	**Porosity (%)**	**Volumetric Moisture (cm^3 cm^{-3})**	**Saturation (%)**	**$\delta^{18}O_{H2O}$ (‰)**	**δH^2_{H2O} (‰)**	**Pore Water Cl (mg L^{-1})**	**+2.0**	**2.0 - 0.42**	**0.42 - 0.21**	**0.21 - 0.105**	**0.105 - 0.074**	**-0.074**
1	East	2006-2009	7/14/2015	0.0	18.0	1.55	47	0.05	10				6.1	12.2	18.8	36.9	12.7	13.3
1	East	2006-2009	7/14/2015	18.0	30.0	1.50	48	0.06	11	-7.79	-56.10	8.7						
1	East	2006-2009	7/14/2015	30.0	44.0	1.48	49	0.11	22	-7.57	-57.35	4.1	9.7	19.3	25.5	29.1	8.4	8.0
1	East	2006-2009	7/14/2015	44.0	55.0	1.54	47	0.06	13	-6.74	-58.23							
1	East	2006-2009	7/14/2015	55.0	61.0	1.24	57	0.29	51	-9.93	-72.32	9.3	7.9	12.3	8.1	14.9	10.5	46.3
1	East	2006-2009	7/14/2015	61.0	74.0	1.45	50	0.11	21	-9.93	-73.07	26.0	2.7	16.9	25.3	34.8	10.8	9.5
1	East	2006-2009	7/14/2015	74.0	88.1	1.46	50	0.14	28	-3.80	-54.56	38.7	2.9	15.0	25.7	36.8	10.5	9.1
2	East	2006-2009	7/14/2015	0.0	18.0	1.44	50	0.06	12			7.2	5.8	14.2	19.9	38.0	12.3	9.8
2	East	2006-2009	7/14/2015	18.0	30.0	1.45	50	0.14	27			7.5						
2	East	2006-2009	7/14/2015	30.0	35.0	1.27	56	0.29	51				0.2	0.6	3.9	29.5	23.1	42.7
2	East	2006-2009	7/14/2015	35.0	45.5	1.39	52	0.39	76			54.1	3.5	3.5	1.6	10.9	17.2	63.3
2	East	2006-2009	7/14/2015	45.5	60.0	1.55	47	0.32	69			80.2	7.5	16.4	26.6	32.6	8.7	8.2
2	East	2006-2009	7/14/2015	60.0	68.8	1.58	46	0.26	56			86.8	11.7	21.6	25.6	28.0	6.5	6.6
2	East	2006-2009	7/14/2015	68.8	74.0	1.58	46	0.29	63			82.5	8.7	23.5	27.7	27.9	6.9	5.3
2	East	2006-2009	7/14/2015	74.0	80.9	1.84	37	0.31	85			83.4	8.0	17.6	24.2	31.4	9.2	9.6
3	East	2006-2009	7/14/2015	0	6	1.41	51	0.40	78	-3.52	-47.17	141.1	5.7	9.9	4.2	5.4	9.2	65.6
3	East	2006-2009	7/14/2015	6	12													
3	East	2006-2009	7/14/2015	12	20	1.45	50	0.39	77	-7.69	-61.11	71.2	0.7	0.6	1.1	22.0	28.1	47.5
3	East	2006-2009	7/14/2015	20	29.5	1.21	58	0.31	53	-7.50	-60.88	75.7	0.0	0.2	2.5	24.1	24.5	48.7
3	East	2006-2009	7/14/2015	29.5	46	1.34	54	0.30	56	-7.38	-60.49	78.8	0.4	3.2	23.5	52.0	12.5	8.4
3	East	2006-2009	7/14/2015	46	52.5	1.52	47	0.34	71	-5.93	-56.44	72.4	0.0	0.7	6.8	49.0	23.1	20.4
3	East	2006-2009	7/14/2015	52.5	65	1.34	54	0.32	60	-5.00	-53.71	75.8	2.8	4.4	9.3	39.3	20.6	23.6
7	West 3	06/2015	7/14/2015	0.0	20.0	1.69	42	0.05	12			16.8	19.4	29.9	20.5	17.6	5.9	6.7
7	West 3	06/2015	7/14/2015	20.0	36.0	1.55	46	0.09	19									
7	West 3	06/2015	7/14/2015	36.0	49.9	1.62	44	0.08	18			73.4	24.1	29.0	20.4	14.7	4.6	7.2

Table A 1 (continued). Hibtac core physical properties and moisture contents.

													Wet Sieve Size Fraction (100 g start weight) (mm)					
Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	$\delta^{18}O_{H2O}$ (‰)	δH^2_{H2O} (‰)	Pore Water Cl (mg L^{-1})	+0.42	0.42 - 0.21	0.21 - 0.074	0.074 - 0.053	0.053 - 0.025	-0.025
1	A1-E	1986	9/17/2014	0.0	6.5	1.18	59	0.16	27					6.6	30.9	19.8	12.5	30.2
1	A1-E	1986	9/17/2014	6.5	13.0	1.28	56	0.06	11			8.7		50.9	31.7	4.2	4.9	8.3
1	A1-E	1986	9/17/2014	13.0	28.5	1.13	61	0.20	32			2.9		23.0	40.4	6.9	11.3	18.4
1	A1-E	1986	9/17/2014	28.5	39.0	1.20	59	0.21	36			5.0						
1	A1-E	1986	9/17/2014	39.0	51.6	1.33	54	0.17	31			6.9		24.8	27.9	7.5	12.3	27.5
1	A1-E	1986	9/17/2014	51.6	62.0							8.4						
1	A1-E	1986	9/17/2014	62.0	75.5	1.32	54	0.26	48			6.0		26.3	41.8	8.1	10.3	13.5
1	A1-E	1986	9/17/2014	75.5	91.5	1.39	52	0.08	15			8.2						
1	A1-E	1986	9/17/2014	91.5	104.3	1.42	51	0.12	23			7.0		25.5	42.5	8.4	9.8	13.9
2	A1-E	1986	9/17/2014	0.0	5.0	1.22	58	0.11	19					1.8	34.0	11.8	19.3	33.1
2	A1-E	1986	9/17/2014	5.0	10.0	1.22	58	0.11	19			3.0		3.7	26.7	15.0	26.4	28.2
2	A1-E	1986	9/17/2014	10.0	24.0	1.21	58	0.20	34	-12.4	-97.2	11.4		4.2	41.1	10.5	16.9	27.3
2	A1-E	1986	9/17/2014	24.0	40.0	1.19	59	0.29	49	-11.1	-78.4							
2	A1-E	1986	9/17/2014	40.0	52.0	1.22	58	0.22	37			11.0		7.1	27.0	7.7	18.0	40.2
2	A1-E	1986	9/17/2014	52.0	64.0	1.33	54	0.10	18			12.3						
2	A1-E	1986	9/17/2014	64.0	70.5	1.00	66	0.21	32					19.1	28.1	5.6	11.6	35.6
2	A1-E	1986	9/17/2014	70.5	73.5	1.36	53	0.43	80	-11.6	-83.0	9.6		0.2	4.6	3.4	13.8	78.0
2	A1-E	1986	9/17/2014	73.5	83.0	1.55	47	0.41	87					1.0	10.6	4.8	15.3	68.3
2	A1-E	1986	9/17/2014	83.0	86.0	1.33	54	0.17	32					32.4	35.9	6.0	8.7	17.0
2	A1-E	1986	9/17/2014	86.0	99.3	1.41	51	0.08	15			14.1		64.1	21.9	2.9	3.3	7.8
3	A2	1989	6/17/2015	0.0	15.0	1.11	62	0.18	28			6.8	0.1	1.5	22.5	9.9	21.5	44.5
3	A2	1989	6/17/2015	15.0	31.0	1.24	57	0.24	43			5.4						
3	A2	1989	6/17/2015	31.0	40.0	1.26	57	0.38	67			5.3	0.0	0.5	6.8	6.0	20.4	66.3
3	A2	1989	6/17/2015	40.0	58.0	1.31	55	0.25	45			9.0						
3	A2	1989	6/17/2015	58.0	70.0	1.37	53	0.17	49			11.3	0.3	6.4	33.6	8.7	18.2	32.8
3	A2	1989	6/17/2015	70.0	81.0	1.29	56	0.27	62			9.1	0.9	6.8	25.9	7.2	16.5	42.7
3	A2	1989	6/17/2015	81.0	92.8	1.27	56	0.35	29			9.1	0.1	1.6	10.9	5.3	16.6	65.5

Table A 2. Minntac fine tailings core physical properties and moisture contents.

Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	$\delta^{18}O_{H2O}$ (‰)	δH^2_{H2O} (‰)	Pore Water Cl (mg L^{-1})	Wet Sieve Size Fraction (100 g start weight) (mm) +0.42	0.42 - 0.21	0.21 - 0.074	0.074 - 0.053	0.053 - 0.025	-0.025
3Dup	A2	1989	6/17/2015	0.0	15.0	1.07	63	0.18	29	-7.6	-62.0	6.2	0.0	3.0	28.8	11.9	20.9	35.4
3Dup	A2	1989	6/17/2015	15.0	29.0	1.26	56	0.20	36	-10.8	-84.1	6.9						
3Dup	A2	1989	6/17/2015	29.0	44.0	1.32	55	0.31	56	-13.5	-104.3	9.7	0.2	2.8	17.8	6.0	16.8	56.4
3Dup	A2	1989	6/17/2015	44.0	55.0	1.33	52	0.28	51	-11.4	-86.9	9.1						
3Dup	A2	1989	6/17/2015	55.0	74.0	1.39	57	0.30	57	-8.3	-68.2	9.1	0.3	4.0	21.9	7.8	17.4	48.6
3Dup	A2	1989	6/17/2015	74.0	94.0	1.26	60	0.32	57	-8.9	-66.7	6.9						
3Dup	A2	1989	6/17/2015	94.0	106.0	1.15	63	0.24	39	-10.8	-82.4	6.4	0.0	0.4	15.7	6.9	17.3	59.7
3Dup	A2	1989	6/17/2015	106.0	120.0	1.06	53	0.26	41	-12.8	-96.3	5.6	0.0	0.0	2.9	5.4	26.2	65.5
3Dup	A2	1989	6/17/2015	120.0	132.0	1.37	49	0.33	63	-13.4	-102.4	5.1	0.0	0.2	10.9	6.0	19.4	63.5
3Dup	A2	1989	6/17/2015	132.0	143.5	1.47	46	0.39	80	-12.6	-96.7	4.7	0.3	0.5	9.2	5.2	16.5	68.3
4	A2	1989	6/17/2015	0.0	18.0	1.31	55	0.06	11			5.2	0.0	5.4	30.4	9.3	19.5	35.4
4	A2	1989	6/17/2015	18.0	30.0	1.25	57	0.15	26			8.7						
4	A2	1989	6/17/2015	30.0	48.0	1.42	51	0.14	28			10.1	3.5	20.0	36.4	6.2	11.5	22.4
4	A2	1989	6/17/2015	48.0	68.0	1.37	53	0.31	60			6.2						
4	A2	1989	6/17/2015	68.0	87.3	1.39	52	0.25	48			5.8	0.8	6.2	21.3	7.2	17.7	46.8
5	A2	1989	6/17/2015	0.0	20.0	1.13	61	0.31	51			3.1	0.2	5.7	24.9	7.3	17.5	44.4
5	A2	1989	6/17/2015	20.0	34.0	1.32	55	0.25	46			5.4						
5	A2	1989	6/17/2015	34.0	44.0	1.41	51	0.44	85			3.8	0.2	1.7	13.1	7.0	18.6	59.4
5	A2	1989	6/17/2015	44.0	54.0	1.53	50	0.36	71			4.1						
5	A2	1989	6/17/2015	54.0	69.0	1.41	52	0.39	76			4.4	0.3	2.2	19.8	6.8	18.0	52.9
6	M2	2013	9/17/2014	0.0	4.4	1.25	57	0.11	20					16.9	39.4	9.0	11.5	23.2
6	M2	2013	9/17/2014	4.4	13.0	1.09	63	0.16	26	-7.6	-57.5	274.6		3.9	20.7	6.8	14.9	53.7
6	M2	2013	9/17/2014	13.0	17.3	1.24	57	0.01	2					22.2	45.5	8.0	10.0	14.3
6	M2	2013	9/17/2014	17.3	22.3	1.42	51	0.10	19					4.0	28.9	8.8	16.1	42.2
7	M2	2013	9/17/2014	0	7	1.37	53	0.14	26					0.3	0.7	1.7	14.3	83.0
7	M2	2013	9/17/2014	7	14	1.25	57	0.35	62	-10.0	-69.2	24.2		0.5	4.7	3.2	11.3	80.3
7	M2	2013	9/17/2014	14	24.5	1.46	50	0.48	96	-11.0	-80.1	56.2		0.2	5.0	2.0	7.9	84.9

Table A 2 (continued). Minntac fine tailings core physical properties and moisture contents.

													Wet Sieve Size Fraction (100 g start weight) (mm)					
Core #	**Cell**	**Date of Last Depostion**	**Sample Date**	**Top Depth (in)**	**Bottom Depth (in)**	**Bulk Density ($g\ cm^{-3}$)**	**Porosity (%)**	**Volumetric Moisture ($cm^3\ cm^{-3}$)**	**Saturation (%)**	**$\delta^{18}O_{H2O}$ (‰)**	**δH^2_{H2O} (‰)**	**Pore Water Cl ($mg\ L^{-1}$)**	**+0.42**	**0.42 - 0.21**	**0.21 - 0.074**	**0.074 - 0.053**	**0.053 - 0.025**	**-0.025**
8	M2	2013	9/17/2014	0	5	0.91	68	0.27	40					0.4	4.4	0.4	2.7	92.1
8	M2	2013	9/17/2014	5	10	1.08	63	0.35	56	-7.5	-62.1	194.8		0.3	5.6	3.9	12.9	77.3
8	M2	2013	9/17/2014	10	14.8	1.40	52	0.38	73	-6.8	-60.4	197.5		0.0	5.7	4.7	16.3	73.3
9	K	2013	6/17/2015	0	16.0	1.32	55	0.15	27			2.4	0.1	1.7	23.4	9.6	21.7	43.5
9	K	2013	6/17/2015	16	35.0	1.38	52	0.22	42			8.7						
9	K	2013	6/17/2015	35	59.0	1.41	51	0.32	62			196.3	0.6	2.8	15.7	7.0	16.9	57.0
10	K	2013	6/17/2015	0	16.0	1.33	54	0.24	45			22.4	0.1	2.7	15.7	5.7	16.4	59.4
10	K	2013	6/17/2015	16	28.0	1.43	51	0.13	26			130.6						
10	K	2013	6/17/2015	28	16.0	1.69	42	0.18	43			186.9	3.6	16.9	35.5	7.1	13.4	23.5
10	K	2013	6/17/2015	32	30.1	1.43	51	0.36	71			66.9	0.1	0.5	7.7	4.5	16.7	70.5
11	K	2013	6/17/2015	0	14.0	1.57	46	0.41	90			339.4	0.1	0.6	5.8	3.0	12.3	78.2
11	K	2013	6/17/2015	14	32.0	1.44	50	0.44	87			149.3						
11	K	2013	6/17/2015	32	28.8	1.47	49	0.46	93			60.7	0.0	0.0	5.1	4.8	17.0	73.1

Table A 2 (continued). Minntac fine tailings core physical properties and moisture contents.

													Dry Sieve Size Fraction (100 g start weight) (mm)					
Core #	**Cell**	**Date of Last Depostion**	**Sample Date**	**Top Depth (in)**	**Bottom Depth (in)**	**Bulk Density ($g\ cm^{-3}$)**	**Porosity (%)**	**Volumetric Moisture ($cm^3\ cm^{-3}$)**	**Saturation (%)**	**$\delta^{18}O_{H2O}$ (‰)**	**δH^2_{H2O} (‰)**	**Pore Water Cl ($mg\ L^{-1}$)**	**+2.0**	**2.0 - 0.42**	**0.42 - 0.21**	**0.21 - 0.105**	**0.105 - 0.074**	**-0.074**
12	Section 11	1985-1990	9/17/2014	0.0	5.5	1.12	62	0.04	7				32.7	48.2	9.8	3.9	1.1	4.3
12	Section 11	1985-1990	9/17/2014	5.5	11.0	1.63	44	0.02	4			10.5	40.4	43.7	9.0	3.2	0.8	2.9
12	Section 11	1985-1990	9/17/2014	11.0	24.0	1.72	41	0.06	15			9.3	39.7	44.1	8.9	3.3	0.8	3.2
12	Section 11	1985-1990	9/17/2014	24.0	38.0	1.72	41	0.06	14			23.7						
12	Section 11	1985-1990	9/17/2014	38.0	50.6	1.64	43	0.06	14			18.4	39.5	46.6	8.5	2.6	0.6	2.2
12	Section 11	1985-1990	9/17/2014	50.6	65.5	1.88	35	0.08	24			26.9						
12	Section 11	1985-1990	9/17/2014	65.5	78.4	1.95	33	0.07	22			146.6	35.0	45.7	9.5	4.1	1.2	4.5
13	Section 11	1985-1990	6/17/2015	0.0	12.0	1.83	37	0.05	14				31.2	48.4	11.1	4.6	1.2	3.5
13	Section 11	1985-1990	6/17/2015	12.0	18.0	1.71	41	0.05	12									
13	Section 11	1985-1990	6/17/2015	18.0	22.0	2.34	19	0.07	36				37.8	44.0	9.5	4.0	1.1	3.6
13	Section 11	1985-1990	6/17/2015	22.0	32.0	1.70	41	0.06	14			28.9	51.3	39.1	5.7	2.0	0.4	1.5
13	Section 11	1985-1990	6/17/2015	32.0	48.0	1.76	39	0.06	15			38.8						
13	Section 11	1985-1990	6/17/2015	48.0	64.0	1.74	40	0.07	17			32.4	32.7	47.2	11.0	4.3	1.2	3.6
13	Section 11	1985-1990	6/17/2015	64.0	83.3	1.70	41	0.08	19			22.4	31.0	48.9	10.3	4.3	1.4	4.1
13Dup	Section 11	1985-1990	6/17/2015	0.0	16.0	1.84	37	0.05	14				33.5	48.3	10.0	4.0	1.0	3.2
13Dup	Section 11	1985-1990	6/17/2015	16.0	28.0	1.89	35	0.05	15			41.0						
13Dup	Section 11	1985-1990	6/17/2015	28.0	44.0	1.78	39	0.06	17			27.6	35.6	49.6	8.2	2.9	0.8	2.9
13Dup	Section 11	1985-1990	6/17/2015	44.0	62.0	1.75	40	0.06	15			31.2						
13Dup	Section 11	1985-1990	6/17/2015	62.0	79.8	1.74	40	0.07	17			29.8	29.8	49.1	10.7	4.3	1.5	4.6
14		2014	9/17/2014	0.0	8.1	1.52	47	0.05	10				26.7	49.6	11.0	4.9	1.5	6.3
14		2014	9/17/2014	8.1	16.0	1.50	48	0.04	8			73.6	27.2	53.2	11.2	4.3	1.1	3.0
14		2014	9/17/2014	16.0	33.5	1.73	40	0.05	12			239.6	25.9	53.9	11.3	4.2	1.0	3.8
15	Fresh Coarse	6/17/2015	6/17/2015	Grab								173.4	15.5	59.8	16.8	5.8	1.1	1.0
15	Fresh Coarse Dup	6/17/2015	6/17/2015	Grab								157.8	26.2	59.6	10.2	3.0	0.5	0.5
16	Coarse	1985-1990	6/17/2015	Grab									48.8	35.6	6.8	2.9	0.9	5.0

Table A 3. Minntac coarse tailings core physical properties and moisture contents.

Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	Pore Water Cl (mg L^{-1})	Wet Sieve Size Fraction (100 g start weight) (mm) +0.42	0.42 - 0.21	0.21 - 0.074	0.074 - 0.053	0.053 - 0.025	-0.025
1	Basin 1	05/2000	7/16/2015	0.0	17.0	1.47	49	0.07	14	10.7	5.6	19.3	41.6	6.6	10.9	16.0
1	Basin 1	05/2000	7/16/2015	17.0	27.0	1.48	49	0.12	24							
1	Basin 1	05/2000	7/16/2015	27.0	40.0	1.59	45	0.08	17	5.0	34.1	22.4	26.3	3.6	6.0	7.6
1	Basin 1	05/2000	7/16/2015	40.0	53.0	1.55	47	0.08	16							
1	Basin 1	05/2000	7/16/2015	53.0	65.0	1.57	46	0.06	13	25.3	43.1	20.9	22.7	2.8	4.0	6.5
1	Basin 1	05/2000	7/16/2015	65.0	78.0	1.57	46	0.06	14							
1	Basin 1	05/2000	7/16/2015	78.0	82.9	1.43	51	0.05	10	51.0	42.8	22.4	20.7	3.0	4.0	7.1
2	Basin 1	05/2000	7/16/2015	0.0	15.0	1.24	57	0.10	17	6.5	0.4	2.9	27.9	10.3	22.2	36.3
2	Basin 1	05/2000	7/16/2015	15.0	27.0	1.28	56	0.22	40							
2	Basin 1	05/2000	7/16/2015	27.0	38.0	1.28	56	0.18	33	1.5	0.0	0.1	16.0	10.8	26.9	46.2
2	Basin 1	05/2000	7/16/2015	38.0	59.0	1.35	53	0.15	29							
2	Basin 1	05/2000	7/16/2015	59.0	74.0	1.38	53	0.17	32	5.4	0.7	7.2	34.6	9.1	15.7	32.7
2	Basin 1	05/2000	7/16/2015	74.0	89.0	1.35	53	0.24	45	5.2	0.4	6.5	20.5	6.4	17.6	48.6
3	Basin 1	05/2000	7/16/2015	0.0	20.0	1.09	62	0.29	46	2.2	0.3	1.1	5.7	3.1	9.9	79.9
3	Basin 1	05/2000	7/16/2015	20.0	32.0	1.31	55	0.31	56							
3	Basin 1	05/2000	7/16/2015	32.0	42.0	1.33	54	0.31	57	1.0	0.0	0.0	1.6	3.0	15.3	80.1
3	Basin 1	05/2000	7/16/2015	42.0	54.0	1.32	54	0.05	10							
3	Basin 1	05/2000	7/16/2015	54.0	64.0	1.32	54	0.37	67	1.8	0.1	0.2	1.0	1.2	7.8	89.7
3	Basin 1	05/2000	7/16/2015	64.0	76.0	1.24	57	0.18	31							
3	Basin 1	05/2000	7/16/2015	76.0	84.6	1.28	56	0.31	56	4.6	0.0	0.1	2.7	4.4	17.6	75.2
4	Basin 2	01/2015	7/16/2015	0.0	15.0	1.58	45	0.05	11	5.6	43.9	27.7	19.0	1.8	2.7	4.9
4	Basin 2	01/2015	7/16/2015	15.0	28.0	1.68	42	0.04	11							
4	Basin 2	01/2015	7/16/2015	28.0	26.4	1.52	48	0.12	25	159.8	32.5	23.3	26.3	4.2	6.0	7.7

Table A 4. Utac fine tailings core physical properties and moisture contents.

Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	Pore Water Cl (mg L^{-1})	Dry Sieve Size Fraction (100 g start weight) (mm) +2.0	2.0 - 0.42	0.42 - 0.21	0.21 - 0.105	0.105 - 0.074	-0.074
5	Basin 1	08/1999	7/16/2015	0.0	14.0	1.71	41	0.03	8		27.2	48.7	12.4	7.2	1.6	2.9
5	Basin 1	08/1999	7/16/2015	14.0	24.0	1.73	40	0.04	9							
5	Basin 1	08/1999	7/16/2015	24.0	34.0	1.68	42	0.03	8		26.5	50.1	11.7	6.7	1.7	3.3
5	Basin 1	08/1999	7/16/2015	34.0	45.0	1.69	42	0.04	10							
5	Basin 1	08/1999	7/16/2015	45.0	55.0	1.73	40	0.06	14	33.5	27.6	47.8	11.6	7.2	1.8	4.0
5	Basin 1	08/1999	7/16/2015	55.0	66.0	1.69	42	0.05	12	17.4						
5	Basin 1	08/1999	7/16/2015	66.0	78.9	1.70	41	0.04	10	29.9	35.5	47.7	8.3	4.3	1.1	3.1
6	Basin 1	08/1999	7/16/2015	0.0	11.0	1.68	42	0.03	9		35.2	43.5	10.1	6.4	1.7	3.1
6	Basin 1	08/1999	7/16/2015	11.0	22.0	1.76	39	0.04	10							
6	Basin 1	08/1999	7/16/2015	22.0	34.0	1.74	40	0.04	9	18.1	42.0	46.7	6.2	2.6	0.6	1.9
6	Basin 1	08/1999	7/16/2015	34.0	43.0	1.72	41	0.05	12							
6	Basin 1	08/1999	7/16/2015	43.0	52.0	1.70	41	0.05	12	16.8	25.1	47.6	12.3	8.3	2.2	4.5
6	Basin 1	08/1999	7/16/2015	52.0	63.0	1.72	41	0.05	13							
6	Basin 1	08/1999	7/16/2015	63.0	74.1	1.69	42	0.08	18	27.9	32.3	47.4	10.0	5.4	1.4	3.5
7	Basin 1	08/1999	7/16/2015	0.0	8.0	1.69	42	0.02	6		47.8	40.4	6.9	3.0	0.6	1.3
7	Basin 1	08/1999	7/16/2015	8.0	19.0	1.86	36	0.03	10							
7	Basin 1	08/1999	7/16/2015	19.0	29.0	1.80	38	0.04	10		47.8	43.9	4.7	1.7	0.3	1.6
7	Basin 1	08/1999	7/16/2015	29.0	36.5	1.74	40	0.04	10							
7	Basin 1	08/1999	7/16/2015	36.5	48.0	1.78	39	0.04	11	29.7	47.1	45.7	4.2	1.2	0.2	1.6
7	Basin 1	08/1999	7/16/2015	48.0	56.0	1.75	40	0.04	10							
7	Basin 1	08/1999	7/16/2015	56.0	68.3	1.77	39	0.04	11	18.7	37.5	43.7	9.0	5.0	1.2	3.6
8	Basin 2	06/2014	7/16/2015	0.0	15.0	1.62	44	0.04	9		18.0	50.3	15.4	10.0	2.5	3.8
8	Basin 2	06/2014	7/16/2015	15.0	26.0	1.63	44	0.04	9	11.8						
8	Basin 2	06/2014	7/16/2015	26.0	40.0	1.63	44	0.04	14	10.7	21.4	46.4	14.4	10.2	2.7	4.9

Table A 5. Utac coarse tailings core physical properties and moisture contents.

Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	Pore Water Cl (mg L^{-1})	Wet Sieve Size Fraction (100 g start weight) (mm)					
											+0.42	0.42 - 0.21	0.21 - 0.074	0.074 - 0.053	0.053 - 0.025	-0.025
1	2A	2000-2001	7/23/2015	0.0	15.0	1.25	57	0.17	30	5.0	0.0	4.4	25.7	9.4	18.3	42.2
1	2A	2000-2001	7/23/2015	15.0	30.0	1.37	53	0.11	22							
1	2A	2000-2001	7/23/2015	30.0	42.0	1.39	52	0.07	14	5.3	1.5	27.8	49.6	4.6	6.3	10.2
1	2A	2000-2001	7/23/2015	42.0	51.0	1.37	53	0.14	27							
1	2A	2000-2001	7/23/2015	51.0	67.0	1.48	49	0.27	55	3.3	0.3	5.5	26.3	7.6	17.7	42.6
1	2A	2000-2001	7/23/2015	67.0	82.0	1.49	48	0.23	48							
1	2A	2000-2001	7/23/2015	82.0	85.1	1.57	46	0.18	39	3.9	0.2	7.0	44.1	12.1	15.7	20.9
2	2A	2000-2001	7/23/2015	0.0	16.0	1.25	57	0.14	25	3.6	0.3	3.6	31.8	8.4	17.3	38.6
2	2A	2000-2001	7/23/2015	16.0	29.0	1.32	55	0.20	37							
2	2A	2000-2001	7/23/2015	29.0	40.0	1.33	54	0.27	49	2.0	0.0	0.9	19.9	7.7	17.1	54.4
2	2A	2000-2001	7/23/2015	40.0	48.0	1.48	49	0.37	77							
2	2A	2000-2001	7/23/2015	48.0	62.0	1.40	52	0.31	61	1.6	0.0	0.5	10.6	6.5	20.5	61.9
2	2A	2000-2001	7/23/2015	62.0	76.0	1.37	53	0.40	76							
2	2A	2000-2001	7/23/2015	76.0	86.6	1.41	51	0.30	58	5.4	0.0	0.7	17.4	6.6	20.2	55.1
3	2A	2000-2001	7/23/2015	0.0	17.0	1.20	59	0.22	37	1.7	0.3	0.3	9.4	5.3	22.8	61.9
3	2A	2000-2001	7/23/2015	17.0	30.0	1.31	55	0.37	68							
3	2A	2000-2001	7/23/2015	30.0	42.0	1.34	54	0.42	78	1.2	0.0	0.0	1.9	2.1	10.2	85.8
3	2A	2000-2001	7/23/2015	42.0	46.0											
3	2A	2000-2001	7/23/2015	46.0	56.8	1.23	57	0.40	70	1.4						
3	2A	2000-2001	7/23/2015	56.8	60.0	1.11	62	0.35	56	1.6	0.0	0.0	0.9	0.8	9.3	89.0
3	2A	2000-2001	7/23/2015	60.0	68.5	1.70	41	0.49	119	1.3						
3	2A	2000-2001	7/23/2015	68.5	77.0	1.35	53	0.32	61	1.1	0.0	0.0	10.3	7.5	25.0	57.2
4	In Pit	2014	7/23/2015	0.0	16.0	1.49	49	0.17	35	281.6	1.1	8.5	30.7	8.3	15.9	35.5
4	In Pit	2014	7/23/2015	16.0	29.0	1.47	49	0.10	20							
4	In Pit	2014	7/23/2015	29.0	40.1	1.60	45	0.19	42	126.5	41.1	9.2	10.7	3.5	11.5	24.0

Table A 6. ArcelorMittal fine tailings core physical properties and moisture contents.

											Dry Sieve Size Fraction (100 g start weight) (mm)					
Core #	Cell	Date of Last Depostion	Sample Date	Top Depth (in)	Bottom Depth (in)	Bulk Density (g cm^{-3})	Porosity (%)	Volumetric Moisture (cm^3 cm^{-3})	Saturation (%)	Pore Water Cl (mg L^{-1})	+2.0	2.0 - 0.42	0.42 - 0.21	0.21 - 0.105	0.105 - 0.074	-0.074
5	2A	1999-2000	7/23/2015	0.0	12.0	1.73	40	0.03	7		17.0	56.9	16.3	6.6	0.9	2.3
5	2A	1999-2000	7/23/2015	12.0	20.0	1.62	44	0.04	8	18.7						
5	2A	1999-2000	7/23/2015	20.0	33.0	1.58	45	0.04	9	14.6	13.4	54.8	17.1	8.9	1.7	4.1
5	2A	1999-2000	7/23/2015	33.0	44.0	1.58	46	0.05	11							
5	2A	1999-2000	7/23/2015	44.0	55.0	1.58	46	0.05	12	16.9	11.3	56.7	18.3	8.5	1.5	3.7
5	2A	1999-2000	7/23/2015	55.0	67.0	1.57	46	0.05	11							
5	2A	1999-2000	7/23/2015	67.0	77.9	1.62	44	0.05	12	14.0	15.9	59.1	13.6	5.8	1.2	4.4
6	2A	1999-2000	7/23/2015	0.0	9.0	1.86	36	0.03	8		24.7	57.1	10.0	4.1	0.8	3.3
6	2A	1999-2000	7/23/2015	9.0	17.0	1.78	39	0.04	9	134.9						
6	2A	1999-2000	7/23/2015	17.0	28.0	1.75	39	0.04	9	203.8	20.6	55.1	11.7	5.8	1.6	5.2
6	2A	1999-2000	7/23/2015	28.0	34.0	1.69	42	0.04	10							
6	2A	1999-2000	7/23/2015	34.0	42.0	1.72	41	0.05	11	125.0	22.4	54.4	10.8	5.4	1.5	5.5
6	2A	1999-2000	7/23/2015	42.0	50.0	1.66	43	0.04	10							
6	2A	1999-2000	7/23/2015	50.0	62.1	1.71	41	0.05	13	117.6	23.0	55.7	10.1	4.8	1.2	5.2
7	2A	1999-2000	7/23/2015	0.0	15.0	1.74	40	0.03	7		18.3	62.3	12.8	4.2	0.7	1.7
7	2A	1999-2000	7/23/2015	15.0	27.0	1.73	40	0.04	10	40.8						
7	2A	1999-2000	7/23/2015	27.0	39.0	1.65	43	0.05	11	29.3	19.1	60.0	12.0	4.4	0.9	3.6
7	2A	1999-2000	7/23/2015	39.0	56.0	1.66	43	0.06	13							
7	2A	1999-2000	7/23/2015	56.0	69.0	1.65	43	0.06	13	43.1	17.2	56.8	13.4	6.1	1.5	5.0
7	2A	1999-2000	7/23/2015	69.0	80.0	1.70	42	0.06	14							
7	2A	1999-2000	7/23/2015	80.0	89.8	1.73	40	0.05	13	86.9	26.5	58.2	7.9	3.2	0.9	3.3
8	2	5-6/2015	7/23/2015	0.0	15.0	1.69	42	0.04	9	28.5	16.5	54.2	14.9	8.5	1.9	4.0
8	2	5-6/2015	7/23/2015	15.0	26.0	1.66	43	0.05	11							
8	2	5-6/2015	7/23/2015	26.0	41.0	1.68	42	0.05	13	55.2	17.9	54.6	13.5	6.7	1.7	5.6

Table A 7. ArcelorMittal coarse tailings core physical properties and moisture contents.

Appendix B

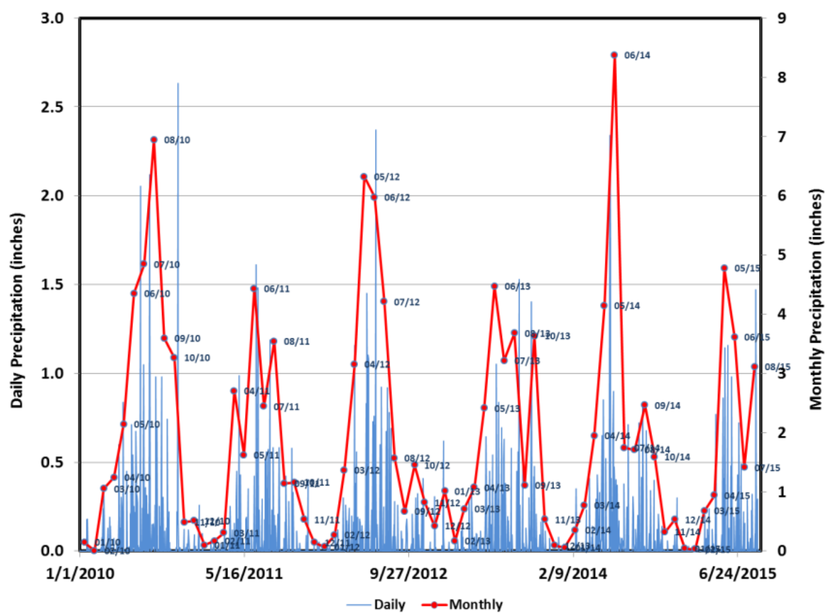

Figure B 1. Daily precipitation measurements used in the HYDRUS-1D model and monthly totals for 2010 – 2015.

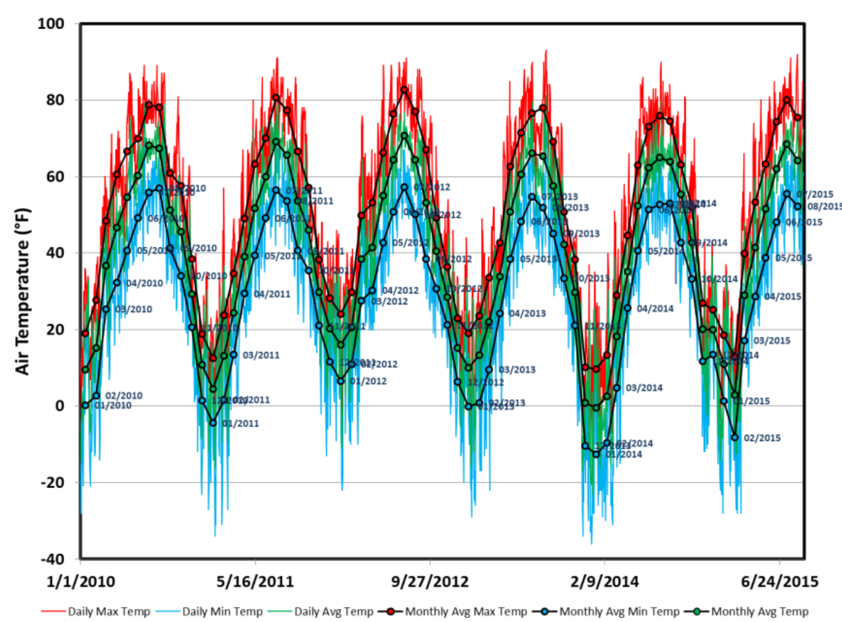

Figure B 2. Daily minimum, maximum, and average temperatures used in the HYDRUS-1D model and monthly averages for 2010 – 2015.

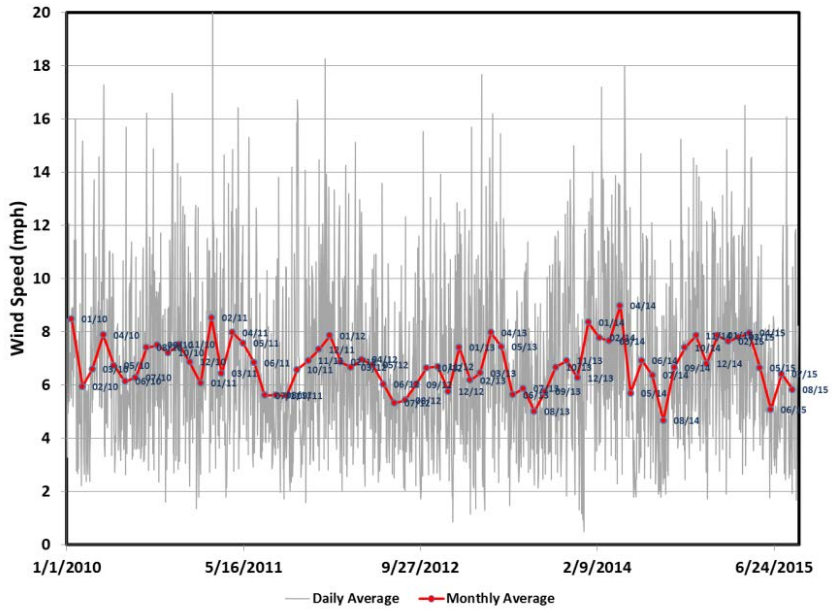

Figure B 3. Daily average wind speed measurements used in the HYDRUS-1D model and monthly averages for 2010 – 2015.

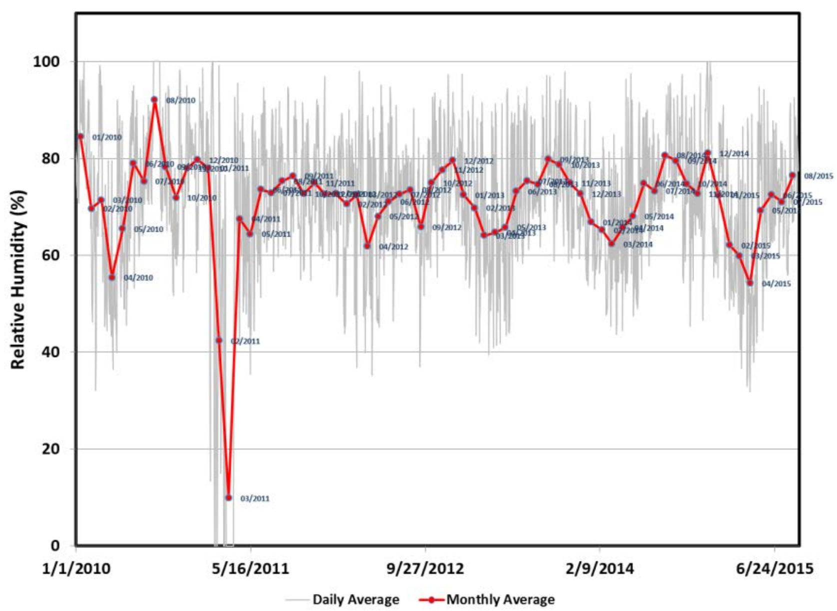

Figure B 4. Daily average relative humidity measurements used in the HYDRUS-1D model and monthly averages for 2010 – 2015.

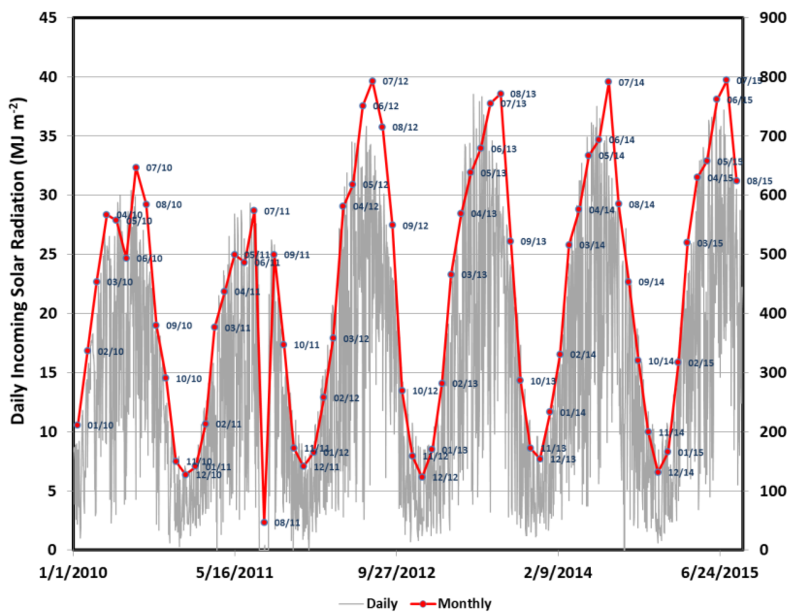

Figure B 5. Daily solar radiation measurements used in the HYDRUS-1D model and monthly totals for 2010 – 2015.

Month	Avg Relative Humidity (%)	Cumulative Precip (in)	Cumulative Incoming Solar Radiation (MJ m^{-2})	Avg Max Temp (°F)	Avg Min Temp (°F)	Avg Temp (°F)	Avg Wind Speed (mph)
01/2010	84.5	0.15	211.0	19.0	0.2	9.6	8.5
02/2010	69.7	0.01	336.1	27.7	2.8	15.3	5.9
03/2010	71.4	1.05	453.4	48.4	25.3	36.7	6.6
04/2010	55.4	1.24	566.7	60.7	32.2	46.7	7.9
05/2010	65.5	2.14	557.0	66.6	40.7	54.5	6.7
06/2010	79.0	4.35	493.3	69.9	49.1	60.3	6.1
07/2010	75.3	4.85	646.6	78.7	55.9	68.2	6.3
08/2010	92.1	6.95	584.3	78.1	57.0	67.5	7.4
09/2010	78.3	3.59	379.4	61.0	41.3	51.3	7.5
10/2010	71.9	3.26	290.4	57.5	34.1	45.5	7.2
11/2010	78.0	0.49	149.7	38.4	20.5	29.3	7.5
12/2010	79.7	0.51	127.3	18.8	1.5	10.8	6.9
01/2011	78.0	0.10	141.2	12.5	-4.4	4.4	6.1
02/2011	42.4	0.17	212.9	23.7	1.6	13.2	8.5
03/2011	9.9	0.31	376.3	34.7	13.4	24.4	6.4
04/2011	67.5	2.70	436.8	49.1	29.4	39.1	8.0
05/2011	64.4	1.62	499.2	63.3	39.4	51.7	7.6
06/2011	73.6	4.43	486.2	70.0	49.2	60.0	6.8
07/2011	72.9	2.44	573.4	80.6	56.4	69.1	5.6
08/2011	75.3	3.54	46.4	77.3	53.7	65.7	5.6
09/2011	76.4	1.14	499.0	66.6	40.6	53.6	5.6
10/2011	72.7	1.16	346.8	57.1	35.4	46.0	6.6
11/2011	75.0	0.53	172.4	38.2	21.0	29.7	6.9
12/2011	72.7	0.14	141.1	28.2	11.5	20.2	7.3
01/2012	72.7	0.07	165.1	24.1	6.6	15.9	7.9
02/2012	70.6	0.27	257.5	29.8	11.0	20.6	6.9
03/2012	72.5	1.36	357.6	49.8	27.5	38.5	6.7
04/2012	61.8	3.15	580.8	53.1	30.3	41.5	7.0
05/2012	68.0	6.32	617.9	66.2	42.8	55.1	6.8
06/2012	71.1	5.98	750.9	76.4	50.8	64.4	6.0
07/2012	72.6	4.21	792.5	82.7	57.3	70.7	5.3
08/2012	73.5	1.57	714.7	77.0	50.1	64.3	5.4
09/2012	65.8	0.67	548.9	67.1	38.5	53.2	6.0
10/2012	75.0	1.45	269.0	49.3	30.8	40.5	6.6
11/2012	77.6	0.82	159.0	36.4	21.2	28.5	6.7
12/2012	79.6	0.42	122.9	23.0	6.3	15.2	5.8
01/2013	72.5	1.01	169.8	19.0	-0.1	10.1	7.4
02/2013	69.8	0.17	281.5	23.6	0.8	13.3	6.2
03/2013	64.1	0.71	465.5	33.6	9.6	22.0	6.4
04/2013	64.7	1.07	568.7	42.7	24.2	33.9	8.0
05/2013	65.8	2.41	637.6	62.6	38.5	50.8	7.4
06/2013	73.2	4.47	678.7	71.6	48.3	60.7	5.6
07/2013	75.4	3.22	755.0	76.6	54.7	66.1	5.9
08/2013	74.7	3.68	771.3	77.9	52.0	65.4	5.0
09/2013	79.9	1.11	521.7	69.2	45.1	57.5	5.8
10/2013	78.7	3.63	286.2	50.8	33.5	42.3	6.7
11/2013	75.0	0.53	172.4	38.2	21.0	29.7	6.9
12/2013	72.7	0.09	154.1	10.2	-10.3	0.8	6.3

Table B 1. Monthly values for climate variables measured at a Minnesota Department of Natural Resources weather station located at the Hibbing-Chisholm Regional Airport.

Month	Avg Relative Humidity (%)	Cumulative Precip (in)	Cumulative Incoming Solar Radiation (MJ m^{-2})	Avg Max Temp (°F)	Avg Min Temp (°F)	Avg Temp (°F)	Avg Wind Speed (mph)
01/2014	66.9	0.06	232.9	9.7	-12.5	-0.4	8.4
02/2014	65.3	0.35	330.4	13.4	-9.6	2.5	7.8
03/2014	62.3	0.77	515.7	29.0	4.8	18.2	7.7
04/2014	65.7	1.95	575.5	44.6	25.6	35.2	9.0
05/2014	68.1	4.14	666.9	63.0	40.6	52.4	5.7
06/2014	74.9	8.38	693.6	73.1	51.4	62.3	6.9
07/2014	73.3	1.74	791.0	75.9	52.7	65.0	6.4
08/2014	80.6	1.71	584.6	74.5	53.0	64.0	4.7
09/2014	79.5	2.46	453.0	63.1	42.8	55.3	6.7
10/2014	74.8	1.59	319.8	52.1	33.3	42.7	7.4
11/2014	72.8	0.32	199.2	27.0	11.7	20.1	7.9
12/2014	81.1	0.53	131.2	25.1	13.4	19.9	6.8
01/2015	72.4	0.04	165.7	18.6	1.3	10.9	7.9
02/2015	62.1	0.03	316.7	12.9	-8.2	2.9	7.6
03/2015	59.9	0.68	519.1	39.9	17.2	29.0	7.8
04/2015	54.2	0.94	629.7	53.3	28.7	41.5	8.0
05/2015	69.3	4.78	657.2	63.2	38.8	51.6	6.6
06/2015	72.5	3.61	761.4	74.4	48.2	62.0	5.1
07/2015	71.1	1.41	794.1	80.0	55.5	68.4	6.4
08/2015	76.5	3.11	623.9	75.4	52.2	64.2	5.8

Table B 1 (continued). Monthly values for climate variables measured at a Minnesota Department of Natural Resources weather station located at the Hibbing-Chisholm Regional Airport.