April 14, 2010

Wild Rice Literature Review Summary

General Summary of Literature Conclusions and Observations

The following is a synopsis of over 40 reports, studies, technical memorandums, and excerpts reviewed for information on the potential effects of sulfate on wild rice as it pertains to the proposed Keetac expansion project. The majority of the documents were obtained from the Project Proposer. Several additional documents, including a recent study conducted by the University of Minnesota – Duluth, a technical memorandum from the Minntac EIS, the 1997 SONAR for state Water Quality Standards, and a thesis on wild rice population cycling were also reviewed.

This summary provides an overview of the biology of wild rice, scientific research on sulfate concentration relative to wild rice health, issues identified during literature review, recent wild rice research in Minnesota, and state rule status in Minnesota and other states.

Biology of Wild Rice

Wild rice (Zizania sp.) is an annual aquatic grass that grows from seed that fell into the water and settled into the sediment during the previous fall. Germination of the seed requires a cold period of dormancy in the bottom substrate where the seeds can remain cool and wet. It is mainly found naturally in the eastern United States with its greatest abundance found in northern Minnesota and northern Wisconsin.

In Minnesota, wild rice typically germinates in late April when water and substrate temperatures reach about 40 degrees F (DNR, 2008). During the first stage of growth, a few weeks after germination, seedlings develop roots and submerged leaves. This is followed by the emergent stage where one or two floating leaves develop, then several aerial leaves form two to three weeks later. In Minnesota, the floating leaves begin to appear in late May to early June, depending on water depth and weather. Natural wild rice typically begins to flower in mid to late July. A staggered seed maturation process occurs over several weeks typically beginning in late August. Once mature, wild rice is ready for harvest or if left to natural processes, will “shatter” and drop its seed, which may remain dormant in the bottom sediment for many years until conditions are favorable for germination.

Certain growing conditions are important factors for wild rice. The literature indicates that water depth (i.e., 0.5 to 3 feet), seasonal water levels (i.e., relatively stable during growing season), water clarity (i.e., clear to moderately stained), and bottom substrate (i.e., soft, organic sediment) influence wild rice production. Even under ideal growing conditions, however, natural wild rice undergoes approximately three to five year cycles in which productivity can vary greatly. Highly productive years are frequently followed by a year of low productivity (DNR, 2008).

Scientific Research on Sulfate Concentrations Relative to Wild Rice

Based on a three-year study completed in 1944, John B. Moyle identified a set of conditions ideal for growing wild rice in Minnesota. These conditions included:

- Clear water, 1 to 3 feet deep, with total alkalinity greater than 40 ppm and sulfate (SO_4) concentration less than 10 ppm;
- Organic soil 6 inches or more in depth, preferably with some calcareous material;
- Some movement of water through the area;

- Fluctuation of water level less than 6 inches throughout the growing season; and
- Absence of carp.

Moyle also indicated that wild rice is intolerant of sulfates and that wild rice is generally absent from water with more than 50 ppm sulfate. Subsequent published studies and reports by Moyle support his original findings. Moyle's findings were used for comparison purposes in this summary.

The literature reviewed for this summary is generally consistent with Moyle's findings for water depth, clarity, soil substrate, water flow (i.e., increases oxygen content of water), and minimal water level fluctuation during the growing season. Ranges given in the literature for water depth, water level fluctuation, soil composition, and clarity were all relatively similar to Moyle's findings, although Moyle was more conservative in his estimates than subsequent studies by other authors. The other literature reviewed for this summary did not discuss the influence of carp on wild rice.

Since 1944, a number of different experiment methods, including in-lake (i.e., natural conditions) to laboratory tests (i.e., buckets and controlled environments), have been used to try to determine a sulfate level detrimental to wild rice. In the literature reviewed, sulfate concentration levels range from 2 mg/L to 3947 mg/L as growing wild rice at various stages, either naturally or in laboratory experiments (see literature review summaries). The Minntac Wild Rice Tech Memo conducted a literature review "suggesting that 'appropriate' sulfate levels for wild rice growth could be bracketed between 10 mg/L and 250 mg/L." The literature review conducted for the Keetac project suggests similar findings with the impression that 10 mg/L sulfate is a conservative concentration limit. Numerous studies indicate wild rice can tolerant significantly higher sulfate concentrations than 10 mg/L without showing adverse impacts to growth or production.

Sulfur in the form of sulfate, nitrogen and phosphorus are all essential nutrients to plants and necessary within a concentration range for healthy plant growth. Literature suggests that sulfate does not act alone to impact aquatic plants. The typical detrimental impacts occur from sulfate when it combines with another element such as magnesium ($MgSO_4$) (Moyle, 1956 and Stewart, 1975), and/or is reduced through anoxic conditions, turning it into hydrogen sulfide (H_2S), which is toxic to aquatic plants and wild rice (Armstrong and Armstrong, 2005; Gao, 2004; MPCA, 1979; Oelke, 1982; Bois Forte, 2001; and MWH, 2004). In studies completed in 1976 and 1978, Peter Lee concluded that a critical level for sulfate was questionable due to its interaction with other chemicals.

Issues Identified During Literature Review

The literature is not conclusive on what chemical parameters and concentration levels influence wild rice growth, either positively or negatively. The literature is also not conclusive on the importance of water chemistry or soil chemistry to wild rice growth. Some studies indicate that water chemistry is not as important as soil/sediment chemistry for healthy wild rice. Moyle found that water chemistry was important and several other studies (Aiken, 1988; Archibold, 1986; Oelke, 1973 and 1982, Bois Forte, 2001; Lee, 2000; Bavin, 2008; Minnesota Power 1981 and 1989; and UMD, 2009) also tested water chemistry, but these did not all support Moyle's findings in regard to sulfate levels, pH, and alkalinity (see literature summaries for specific details). Other studies examined sediment chemistry specifically (i.e., Grava, 1974 and Peden, 1982). All literature seems to conclude that during its early stages of growth, water levels and fluctuation have the greatest effect on wild rice, rather than the chemistry of the environment.

There are numerous studies that dispute Moyle's conclusions regarding sulfate concentration impacts on wild rice and very few published studies that support Moyle's findings regarding sulfate level concentrations of 10 mg/L as effecting wild rice. The studies that support Moyle's findings typically do so by citing Moyle's 1944 study in text that discusses other factors related to wild rice growth, such as water depth, but do not provide supporting data of their own confirming that sulfate levels above10 mg/L effect wild rice.

The most recent published research in Minnesota on sulfate impacts on wild rice was completed by the University of Minnesota – Duluth (UMD) and Montgomery Watson Harza (MWH) for the Minntac EIS. UMD conducted controlled experiments using wild rice planted from seed in five gallon buckets located outdoors for one growing season. Their experiment findings supported Moyle's sulfate concentration level of 10 mg/L as having an effect on wild rice production, although some data was considered not statistically significant. The Minntac EIS wild rice tech memo prepared by MWH used water quality data collected by the Bois Forte Band and literature review to determine that "impacts of excess sulfate on wild rice germination, growth, and kernel yield are not clear." However, the MWH did conclude that highly concentrated sulfate water has played a role in the decline of wild rice overtime in the Sandy River, and that other chemical and geophysical factors may have also contributed to the loss. Minntac tailings basin discharge water has an average concentration of over 700 mg/L.

State Rule Status

Several states have begun to look at their state water quality standards as part of the federal Clean Water Act (CWA). Minnesota is currently reviewing its water quality rules. Some states have recently updated their state water quality standards, specifically their sulfate concentration criteria, including Illinois and Indiana.

Minnesota

Statewide water quality standards were first adopted in Minnesota in 1967. In 1972, the CWA required the MPCA to amend some of its original water quality standards. Every three years the federal CWA requires states to obtain public comment on, and revise as needed, their water quality standards. This is considered a triennial review.

The MPCA adopted a sulfate standard in 1973 of 10 mg/L (Office of Administrative Hearings, 1997). In 1997, a formal rulemaking process to amend Minnesota Rules Chapter 7050 was completed. The SONAR for that process indicated that the numeric sulfate standard was not modified, but that wild rice waters were designated in the Lake Superior Basin in Part 7050.0470 and a narrative describing the importance of wild rice was added to Part 7050.0224. Minnesota Rules Chapter 7052 was also adopted during the 1997 rulemaking process. These rules were adopted as part of the Great Lakes Water Quality Initiative to implement nondegradation standards for pollutants to the Lake Superior Basin.

In July 2008, the MPCA began the triennial review process as part of CWA requirements. The proposed water quality standards amendments will be to Minnesota Rules chapters 7050 and 7052. Rule changes under consideration, among others, include re-evaluation and updates to the Class 4 (agriculture and wildlife) water use standards, which "shall be used as a guide in determining the suitability of the waters for such uses." The Class 4 standards include sulfate concentration limits of "10 mg/L, applicable to water used for the production of wild rice…" Minnesota Rules, part 7050.0224, subpart 2. MPCA plans to complete the water quality standards rule amendments in 2011.

Illinois

Illinois Rules Subtitle D, Part 405, Section 406.100(d) – Mine Waste Effluent and Water Quality Standards (NPDES Permits) was approved by EPA in March 2009 to eliminate the exemption mine discharge has to water quality standards. Illinois Rules Section 302.208(g) – Chemical Constituents were also revised. Sulfate concentration standards were revised, except for receiving waters for which mixing is allowed under Section 302.102. For water used for livestock watering, the sulfate standard was set at 2000 mg/L. Additionally, an equation to determine sulfate limits based on water hardness (calcium carbonate) and chloride concentrations was created. For example, if the hardness concentration of water is less than 100 mg/L or chloride concentration of waters is less than 5 mg/L, the sulfate standard is 500 mg/L. Additional information on Illinois Rule sulfate standard revisions can be found on the Region 5 EPA website: http://www.epa.gov/R5water/wqs5/decisions.htm.

Indiana

Indiana submitted proposed state rule revisions to EPA for its state standard for sulfate (Rule 327 IAC 2-1-6) which consists of a new aquatic life criterion for sulfate. The revisions were approved by EPA in November 2008.The previous Indiana sulfate criterion of 1,000 mg/L applied to all surface waters outside mixing zones. The new criteria varies depending upon water hardness and chloride concentrations in the surface water, and is expressed as an equation (i.e., similar to the state of Illinois). The purpose of the revision was to incorporate new toxicity data and a better scientific understanding of the relationship between sulfate toxicity and hardness and chlorides for individual water bodies. More information can be found on the Region 5 EPA website: http://www.epa.gov/R5water/wqs5/decisions.htm

Iowa

Using Illinois as a model, Iowa Department of Natural Resources proposed an aquatic life protection level for sulfate concentration of 2000 mg/L. In its rulemaking process, Iowa compared itself as being similar to Illinois in regard to total dissolved solids and its relationship to sulfate and chloride concentration levels. Iowa DNR also used the 2006 Draft Justification for Changing Water Quality Standards document from the Illinois Environmental Protection Agency in their rulemaking process.

Wisconsin

Similar to Minnesota, Wisconsin Department of Natural Resources began its Triennial Standards Review process in the April 2008 and examining their surface water quality standards for potential state rule revisions, which does not appear to include sulfate criteria.

Wisconsin Triennial Standards Review Process
http://dnr.wi.gov/org/water/wm/wqs/tsr/documents/TSRProcessFINALREV06-19-2008.pdf

Wisconsin Chapter NR 140 regulates groundwater quality. It includes standards for sulfate, which are set at 250 ppm for the Enforcement Standard and 125 mg/L for the Preventative Action Limit (i.e., trigger point for early evaluation for potential groundwater contamination. More information on WIDNR groundwater quality as it relates to mining can be found in *Protecting Groundwater at Metallic Mining Sites* (WIDNR, 2003; website: http://dnr.wi.gov/org/aw/wm/mining/metallic/infosheets/gwa-pro.pdf).

Montana

The following is an excerpt taken from Montana Department of Environmental Quality Circular DEQ-7: Montana Numeric Water Quality Standards, dated August 2010. The document provides the proposed state water quality rules and information. Circular DEQ-7 does not list a specific concentration limit for sulfate.

> *Both Montana's surface water and groundwater rules contain narrative standards (ARM 17.30.620 through 17.30.670 and ARM 17.30.1001 through 17.30.1045). The narrative standards cover a number of parameters, including sulfate…for which sufficient information does not yet exist to develop specific numeric standards. These numeric standards are directly translated to protect beneficial uses from adverse effects, supplementing the existing numeric standards.*

More information on Montana's current water quality standards revision process can be found on the Montana DEQ website: www.deq.state.mt.us/wqinfo/standards/default.mcpx

Wild Rice Literature Review Summary

Literature Summaries by Author

Aiken

(1) Aiken, S.G., P.F. Lee, D. Punter, and J.M. Stewart. 1988. *Wild Rice in Canada.* Toronto: New Canada Press Ltd., pages 41-42.

The excerpt from this study discusses water quality requirements for wild rice. Based on a survey conducted of northwestern Ontario and northeastern Minnesota lakes, it was concluded that wild rice grows in two types of lakes: those with an alkalinity of about 40 mg/L and pH values of about 6.9 (similar to Moyle's findings); and those lakes with an alkalinity of about 80 mg/L and pH values of 7.4 (similar to Lee's findings). This study cites Moyle's conclusions about wild rice not occurring in lakes with sulfate levels above 10 mg/L, but goes on to provide information to the contrary.

> *Evidence exists that wild rice absorbs most of its required nutrients from the soil, which suggests that water chemistry is only indirectly important. In controlled greenhouse studies, sulfate concentrations in the water overlying a silica sand substrate, described by Moyle as adversely affecting wild rice, were shown to have no effect on wild rice growth (Lee and Stewart, Unpubl. Rep. 1978). In another study (Davis, 1979) an average sulfate concentration of 170 was found in the water of very productive wild rice paddies along the Clearwater River in Minnesota.*

The study excerpt provides additional information on soils for growing wild rice.

Archibold

(2) Archibold, O.W. and B.J. Weichel. 1986. Variation in wild rice (Zizania palustris) strands across northern Saskatchewan. *Canadian Journal of Botany* 64:1204-1211.

The purpose of this study was to determine site selection criteria for successful wild rice seeding programs in Saskatchewan. The methods used in this study to assess wild rice health included taking measurements at 20 sites across northern Saskatchewan of stem density, flowering stages (floret emergence), panicle development, tillering, seed weight, and root and shoot biomass.

The study did not examine sulfate, but instead looked at pH, water levels and depths, water temperature, and geographic range within Saskatchewan. The study concluded that:

> *Plant development was more rapid in the eastern part of the province, and harvest began about 1 week earlier here. However, in the west, individual plants were typically more robust, tillering was more common, and the number of florets borne on the panicle was generally larger. Consequently, potential seed production from an individual plant was highest in these western districts, although differences in stem density and seed weight at the various sites offset individual plant performance to some extent. Differences in water temperature and water depth occurred across the province in July, while in August, water depth, pH, and conductivity were significantly correlated with longitude. Water depth and pH were most strongly related to plant performance, shallower water and higher pH being characteristic of the western sites.*

Cullen

(4) Cullen, Richard. 1973. Paddy production of wild rice. *Technical Notes, Agronomy* No. 13.

This study provides an overview conditions necessary to develop wild rice paddies for commercial production, including dike construction, irrigation, pumping, and drainage requirements. It does not discuss sulfate concentrations.

Grava

(5) Grava, John, and Kennth F. Rose. 1974. *Soil fertility and chemistry aspects of wild rice production—a progress report.* St. Paul: University of Minnesota, Department of Soil Science.

This progress report discussed observations made regarding soil chemistry and temperature at the Clearwater Rice Company wild rice paddies in the early 1970's. The report discusses fertilization of wild rice, nutrient uptake (nitrogen and phosphorus) by the plants, and bases the success of wild rice stands on harvest yields. The report does not discuss sulfate concentrations.

Possible additional reference by Grava to consider reviewing as referenced by Lee:

- Grava, John. 1983. Wild Rice in Clearwater River. Bulletin.

Court Case – Lac Courte Oreilles Band vs. Wisconsin

(6) *Lac Courte Oreilles Band of Lake Superior Chippewa Indians v. State of Wisconsin.* 1989. Wild rice regulatory phase consent decree. Case No. 74-C-313.C.

This document outlined the court case between the Lac Courte Oreilles Band of Lake Superior Chippewa and the State of Wisconsin and its subsequent ruling. The court ruling did not address sulfate concentrations. However, the document provides a good overview of the biology of wild rice in Wisconsin. Main purpose of this Consent Decree appears to address enforcement actions within the state and uphold the Band's usufructory rights for wild rice harvest.

Lee

(7) Lee, P. and J. M. Stewart. 1976. *Effects of the Clay-Boswell Power generating station on strands of wild rice on the Mississippi River.* Winnipeg: University of Manitoba Department of Botany

(8) Lee, P. and J. M. Stewart. 1978. *Impact of sulfate discharge from the Clay Boswell steam electric station on the ecology of wild rice strands on the Mississippi River.* Winnipeg: University of Manitoba Department of Botany.

A two-year study was undertaken by Minnesota Power as part of their NPDES discharge permit for the Clay Boswell stream electric generating plant. The study entailed surveying wild rice stands at five sampling locations along the Mississippi River near the discharge of the Clay Boswell plant, both upstream and downstream of the discharge.

The study included a literature review of the potential impacts of sulfate on wild rice. The conclusion of the literature review was that the standard of 10 mg/L is not proven by the literature and that a survey of wild rice in Minnesota will result in sulfate concentrations of both less than and in excess of 10 mg/L of sulfate at the same site because sulfate concentrations vary seasonally within water bodies.

The specific objectives of the field and laboratory study included:

- Determining the factors which stimulate or depress the growth and distribution of wild rice;
- Isolating the effect of discharge effluent, particularly sulfates, from the facility on wild rice growing downstream compared to plants growing upstream.

Samples of wild rice plants, water quality and sediment parameters were collected from five stations along the Mississippi River at bi-weekly intervals in 1976 and 1977. Stations 1 and 2 were above the Clay Boswell plant discharge, station3 was in the effluent canal, station 4 was within the intermixing discharge and station 5 was 800 meters downstream of the plant discharge. Station 3 was not part of the natural rice beds within the river and was very different from the other sampling stations so the results were not part of the final analysis.

Multivariate statistics were used (e.g., cluster analysis, discriminate analysis) to identify factors that influence the growth of wild rice across the four monitoring stations (1, 2, 4, and 5). The final conclusions of the analysis determined:

- The factors that most influenced wild rice growth in the Mississippi River included water temperature, water depth, wild rice density and a chemical factor of interrelationships of chemical elements in the water and sediment.
- Under natural field conditions, no chemical element, including sulfate was able to be isolated from other chemical factors, and therefore no specific element could be identified as the main factor influencing wild rice growth.
- Seasonal trends exist in sulfate concentrations, indicating that sulfate samples taken at only a single time would not accurately reflect the range of sulfate concentration present at that sample station.
- Sulfate concentrations in the water reached levels of 120 mg/L without showing signs of effecting wild rice growth.
- Sulfate concentrations available in sediment were very high, ranging up to 1200 mg/kg, but did not appear to influence wild rice growth. Sediment concentrations of sulfate, as well as other elements, varied widely across and within sampling stations.
- Sulfate uptake from the sediment by wild rice plants appeared to be a function of other elements, including magnesium and calcium, and not a function of the sulfate concentration in the sediment.
- Under experimental conditions in the laboratory, there was trend of an increase in the weight of wild rice plants up to a concentration of 200 mg/L. There was a large variance within the data from the wild population of wild rice used, and as a result it was not possible to determine critical high or low values for sulfate for normal wild rice growth.

- A survey of over 40 wild rice lakes within 80 km of the plant found the average sulfate concentration in the water to be 10.95 mg/L, but there was a large standard deviation of 8.8 mg/L and a total range of 2 to 59 mg/L.

Overall, the final conclusion was that the establishment of a critical level for sulfate is questionable without taking into account the temporal and spatial variance as well as its interaction with other chemicals. The study found no evidence to support that level of sulfate above 10 mg/L or up to and including the elevated levels observed within the study have a detrimental effect on wild rice.

(9) Lee, P.F. and J.M. Stewart. 1983. 1. Ecological relationships of wild rice, Zizania aquatica. 2. Sediment – plant tissue nutrient relationships. *Canadian Journal of Botany* 61: 1775-1784.

Harvest wild rice plants from four quadrants within the Mississippi River near the Clay Boswell Stream Electric Generating Station near Cohasset, Minnesota. Stations were both up and downstream of the power plant, including within the mixing zone and adjacent to the main coal storage area. Plant samples were collected on bi-weekly intervals from May through September in 1976 and 1977.

The study tested for ten parameters within the sediment and plant tissue (roots, leaves, and stems) of wild rice plants including nitrogen, phosphorus, potassium, sulfur, iron, manganese, zinc, copper, calcium and magnesium. There was wide variation in the sediment concentrations within sampling stations, which was attributed to actual variations in the river sediment due to currents. The variations in the sediment concentrations did not result in much variation within the plant tissue concentrations. The results of the experiment found that there were no significant positive correlations between leaf and sediment concentrations for magnesium, manganese, and zinc, and there were negative correlations of iron and copper. Therefore, high nutrient concentrations did not cause higher leaf tissue concentrations. The study found that seasonal trends in wild rice plant tissue concentrations of nutrients exist. However, even with development of a model to remove the seasonal variation, a correlation between sediment concentration and tissue concentration still does not exist.

(38) Lee, Peter. June 2000. The Effects of Sulfate on Early Development of Wild Rice.

US Steel commissioned Dr. Peter Lee, through Lakehead University in Thunder Bay, Ontario, to conduct a study on the effects of sulfate on wild rice. This study was completed in June 2000. The study contains two main elements: 1) literature review of studies or publications examining concentrations of sulfate in water bodies that contain wild rice; and 2) determination of impacts of varying sulfate concentrations on early stage development of wild rice plants.

Part 1: Literature Review

- Moyle reported finding occurrence of wild rice in sulfate concentrations of up to 282 mg/L during his study even though he stated 10 mg/L is the limit for healthy wild rice. He later concluded that the distribution of aquatic plants in Minnesota could be related to “the toxicity of magnesium usually associated with sulfates” (Moyle, 1956).
- Rogalsky (1971) advised that 200 mg/L was the acceptable concentration for growing wild rice in paddies.

- Grava (1983) reported that sulfate levels typical in Minnesota waters do not injure wild rice, with wild rice fields along the Clearwater River ranging from 22-390 mg/L.
- Pip (1984) examined the distribution of 59 species of aquatic plants in Minnesota stating that pH, TDS and total alkalinity to be the factors limiting distribution with chloride, phosphorus and sulfate concentrations reported as being "of minor importance in both areas."
- Lee and Stewart (1978) showed an increase in dry weight of wild rice grown in sand culture with increasing sulfate concentrations up to 400 mg/L but there was a wide variation in the data set.
- Malvich and Percich (1993) used 48 mg/L for their wild rice hydroponic culture.

Literature review conclusions:

- There are a limited number of controlled experiments examining the influence of sulfate.
- Wild rice has been reported growing in water bodies with sulfate concentrations ranging from 2 – 1333 mg/L.
- Based on observational studies, there is no agreement across the studies on the threshold level where sulfate becomes toxic to wild rice.
- There is a limited amount of controlled experiments on the effects of sulfate on wild rice, and the results do not demonstrate the levels of sulfate that are toxic to wild rice.

Part 2: Experiments to Determine Sulfate Impacts on Wild Rice
Four experiments were conducted in 2000 related to sulfate influence on the early stages of wild rice growth. In all experiments, wild rice plants were grown from seeds. The experiments compared the root and leaf growth of wild rice plants across various sulfate concentration treatments at Day 1, 7 and 14. A description of each type of experiment follows.

1. Sulfate Free Test compared wild rice growth in solution free of sulfate to standard wild rice growth media developed by University of Minnesota with 39 mg/L.
2. Minntac water (US Steel water) vs. standard growth media. US Steel water has very high sulfate (552 mg/L) but is very low in necessary nutrients (phosphorus, nitrogen, and potassium).
3. Range finding test compared growth of wild rice in various sulfate solutions at concentrations of 41, 139, 239, 549, 1058 and 2106 mg/L.
4. Sulfate definitive test compared growth of wild rice in various sulfate solutions of 35, 1508, 1886, 2450, 2968, 3453 and 3947 mg/L.

The study concluded the following:

- Leaf area growth decline was an indicator of nutrient imbalance regardless of whether the nutrient was too high or too low.
- Leaf area growth was greater in sulfate concentrations of 139, 239 and 549 mg/L than in the control solution of 35-40 mg/L of sulfate.
- Leaf growth in the US Steel water was less than in the control water even though the concentration of 552 mg/L of sulfate was similar to the treatment of 549 mg/L that exhibited the second highest leaf growth. It was concluded that other deficiencies in the nutrient poor US Steel water were the cause of the reduced leaf growth and not sulfate levels.

- Sulfate concentrations between zero and the control solution (35-40 mg/L) result in sulfate deficiencies in plant tissue and should be considered limiting concentrations.
- Experiment 4 (the definitive test) showed little effects on wild rice until sulfate concentrations reached 1508 mg/L. Concentrations below this level should be considered suitable for wild rice.
- Experiment 4 also showed that abnormal wild rice growth in both leaves and roots did not occur until sulfate concentrations reached 3947 mg/L, and based on this test, a level of 3453 – 3947 should be considered detrimental to wild rice growth.

Meeker

(11) Meeker, James E. 1993. The ecology of "wild" wild rice (zizania palustris var. palustris) in the Kakagan Slough, a riverine wetland on Lake Superior. Ph.d thesis, University of Wisconsin, Madison.

Meeker describes the life history of wild rice, including growing conditions, seasons, temperatures, pollination, competition, disturbance, substrate quality, and nutrients. There is limited discussion on water chemistry, but states, "Large-scale testing of water chemistry in the Kakagon slough has indicated only slight variability over a wide area and does not appear to be an important factor in wild rice distribution in this system." The study concludes that wild rice distribution is correlated to water depth and fluctuations of that depth within the Kakagon slough system. Rapid water depth changes can damage the early growth of wild rice.

Minnesota Department of Natural Resources

(3) Bavin, Travis, and Michael Berndt. 2008. *Sources and Fate of Sulfate in NE Minnesota Watersheds: A Minerals Coordinating Committee Progress Report.* St. Paul: Minnesota Department of Natural Resources, Division of Lands and Minerals.

This document is a DNR Mineral Coordinating Committee progress report on a two-year study (2007-2009) examining the source and fate of sulfate in northeastern Minnesota watersheds. A survey was conducted in September 2007 of the St. Louis River and eight of its major tributaries, sampling for sulfate (SO_4), sulfur (S) and oxygen isotope ratios for dissolved SO_4 molecules, total Hg (THg), methyl Hg (MeHg), dissolved organic carbon (DOC), and many other dissolved species.

> *Initial sampling found that the SO_4 inventory for the river is complex and involves multiple sources, not all of which were adequately determined in the initial sampling round. THg and MeHG concentrations in the initial survey exhibited little, if any, correlation with SO_4 concentration but suggested, instead, strong correlation with DOC and total wetland area in the non-mining impacted streams and with chloride (Cl) in the mining impacted streams.*

Additional sampling was scheduled to be conducted in 2008 and 2009. The study was scheduled to be completed by June 30, 2009.

Much of the progress report/study focuses on the effects of sulfate concentrations and its relationship to mercury. Comparisons are made between water bodies near the center of mining activity (Virginia, Minnesota) and how concentrations decline as you move west and east along the Iron Range. Average SO_4 concentrations in nearby lakes and rivers range between 2 mgL^{-1} and 232 mgL^{-1}. SO_4 concentrations in water bodies outside of mining areas are less than 10 mgL^{-1}.

As it specifically relates to wild rice, the study cites several additional studies (Armstrong and Armstrong, Gao, et al., and the Minntac EIS). These studies indicate that:

> *Under anoxic conditions, SO_4 can be reduced to sulfide, which, at high concentrations, can cause suberisation and cell wall thickening in adventitious and lateral roots. Suberisation and the thickening of the cell wall can reduce the ability of the rice plants to take up oxygen, water, and Fe^{2+} (Armstrong and Armstrong, 2005), which can stunt their growth and yields (Gao et al., 2004).*

The progress report acknowledges the debate about the SO_4 level that wild rice can tolerate before it becomes toxic, and refers to the 10 mgL^{-1} sulfate standard. The progress report cites the Minntac EIS information regarding the Sandy River study that measured sulfate concentrations in the wild rice beds of 118 (water concentration) and 275 (sediment concentration) mgL^{-1}. The report indicates "experimental evidence has shown that buildup and decomposition of rice residue after senescence can create environmental conditions conducive to SO_4 reduction and can potentially exacerbate sulfide toxicity (Gao et al., 2004)."

Possible additional studies to review for sulfate effects on wild rice as referenced in Bavin:

- Armstrong, A., and Armstrong, W. 2005. Rice: Sulfide-induced barriers to root radial oxygen loss, Fe^{2+} and water uptake, and lateral root emergence. Annual of Botany 96, 625-638.

- Gao S., Tanji, K.K., and Scardaci, S.C. 2004. Impact of rice straw incorporation on soil redox status and sulfide toxicity. Agronomy Journal 96, 70-76.

- Minntac. 2004c. Minntac Water Inventory Reduction Final EIS Wild Rice Tech Memo. U.S. Steel Corporation, Pittsburgh, PA, 58 p. (reviewed as part of this summary, see below)

(12) Minnesota Department of Natural Resources. 2008. *Natural Wild Rice in Minnesota.* Wild rice study document submitted to the Minnesota Legislature.

The excerpt from this study (provided by Barr Engineering) was brief and generally described potential impacts mining can have on wild rice. These impacts included exceeding the state sulfate standard of 10 mg/L, including tailings basin seepage being measured as high as 1,000 mg/L. The excerpt did not discuss how the exceedance of the state standard specifically impacts wild rice. The excerpt also described how mining activities alter the hydrology of an area through pumping and dewatering of mine sites, which can impact wild rice by changing water levels in basins where it may be growing.

Minnesota Pollution Control Agency

(13) Minnesota Pollution Control Agency. Division of Water Quality. Planning Section. 1979. *Impacts of Commercial Wild Rice Production on Water Quality in Minnesota.* Roseville, MN.

This was a brief excerpt from an MPCA report related to sulfur on Clearwater Rice (CWR) paddies in northwestern Minnesota. It states that:

> *Reduction of sulfate to sulfide is brought about by species of the bacteria Desulfovibrio, and is important in submerged soils because H_2S is toxic in plants. Toxicity of H_2S is most prevalent in soils high in organic matter and low in iron.*

It cites Moyle's conclusions on sulfate concentrations related to wild rice growth, but it also cites a study completed for CWR paddies along the Clearwater River (Trippler, et al., 1977) that observed wild rice growing in water with sulfate concentrations between 22 to 170 mg/L. Also lists another study that recommends that state water quality standards for sulfate on wild rice be increased or dropped (Lee and Stewart, 1978).

(14) Minnesota Pollution Control Agency. 1990. Letter to Minnesota Power. July 1990.

A letter from MPCA to Minnesota Power concurs that a four-year study, completed by Minnesota Power, demonstrated that the Clay Boswell Plant discharge was not impacting wild rice stands in the river. The MPCA approved Minnesota Power's request to discontinue the wild rice study, which was a requirement under their NPDES permit.

(15) Minnesota Pollution Control Agency. Office of Administrative Hearings. 1997. *Report of the administrative law judge in the matter of proposed amendments to rules governing water quality standards for protection and purity, Minn. R. Ch. 7050; and proposed new rules governing water quality standards, standard implementation, and nondegradation standards for Great Lakes Initiative pollutants in the Lake Superior Basin, Minn. R. Ch. 7052.* MPCA Document no. 6-220-11246-1. St. Paul, MN.

This administrative law judge (ALJ) report summarized the rule proceeding in 1997 regarding proposed amendments to state water quality standards. An excerpt specifically related to wild rice was reviewed. The ALJ distinguishes between natural wild rice and cultivated wild rice. The rule proceedings and amendments were focused on protecting natural wild rice stands. These included listing 24 water bodies, all of which are located in the Lake Superior Basin, as wild rice waters (having natural wild rice that should be protected).

The ALJ report also indicates that the MPCA "intends, in the future, to identify additional wild rice waters on a statewide basis. In the future, the Agency also intends to integrate wild rice BMPs into the existing BMPs already used by state and local agencies in connection with their permit-granting functions…" Concern was raised by a number of cultivated growers and coalitions that the rule amendments would impact cultivated wild rice activities. The proceeding emphasized that "The changes proposed in this proceeding were all aimed at protecting natural wild rice habitat and production, as opposed to cultivated paddy-based wild rice habitat and production."

Additionally, cultivated wild rice growers expressed concern over the 10 mg/L sulfate standard for wild rice lakes, believing it to be a new amendment, and arguing that the standard is based on outdated data. “The Agency also acknowledged the existence of the more recent data and stated that it would re-evaluate the sulfate standard and might make changes to it in subsequent rulemaking proceedings.”

The ALJ urges the Agency to remember the distinction between natural wild rice and cultivated wild rice when they proceed forward with developing BMPs and listing additional wild rice waters, as the two groups should not be treated the same in state rules.

Minnesota Power

(16) Minnesota Power. 1981. *EPA general information consolidated permits form.* (14 April 1981). Duluth, MN.

Minnesota Power submitted a consolidated permits report to the USEPA related to its NPDES permit and air permit for operation of its Clay Boswell facility. The report discusses sulfate in the power plant discharges and refers to previous studies that were completed by Lee in regard to sulfate concentrations and impacts to wild rice. At that time, Minnesota Power wanted to convert from the use of hydrochloric acid in its cooling towers to the use of sulfuric acid. Minnesota Power indicated that based on past literature and studies done at the facility, “sulfate concentrations in the Mississippi River would increase only slightly if conversion to sulfuric acid was implemented.” It further stated that “laboratory results submitted in the 1978 report also indicated that sulfate levels as great as 200 ppm would not harm the wild rice beds near the steam station.”

The effluent limits at that time were 60 ppm (June 16 to April 14) and 40 ppm (April 15 to June 15) at the Cohasset Bridge. Minnesota Power was requesting that the effluent limits be increased to 70 ppm 365 days per year on the basis that monitoring data and literature review indicated that there would be no detrimental effects to wild rice at that concentration.

(17) Minnesota Power. 1989. *Unit 3 fly ash pond discharge environmental studies for the Clay Boswell electric steam station.* Duluth, MN.

This report provided the results of sediment surveys conducted in 1986, 1987, 1988, and 1989 as part of the 1985 Minnesota Power NPDES permit for discharge of treated supernatant from the Unit 3 fly ash pond at the Clay Boswell facility and their potential impact on wild rice beds in the Mississippi River downstream of the facility. The report indicated that the chemistry of the river water was affected by the Boswell Steam Station discharge. However, “this observation was similar to those made in past Boswell Annual Environmental Monitoring Reports. River sediments in the rice beds, wild rice tissue chemistry and abundance, and wild rice head chemistry did not demonstrate an impact from the Unit 3 fly ash pond discharge.” This was determined through sediment analysis, wild rice plant biomass sampling, and water quality analysis. Wild rice plants were analyzed for extractable sulfate (SO_4), arsenic (As), calcium (Ca), chromium (Cr), copper (Cu), lead (Pb), magnesium (Mg), and nickel (Ni). Water quality samples were analyzed for a number of different parameters including total sulfate (SO_4) concentrations.

A literature review for wild rice was provided, which was taken directly from the 1978 report and previously described under (8) Lee, P. and J. M. Stewart. 1978. *Impact of sulfate discharge from the Clay Boswell steam electric station on the ecology of wild rice strands on the Mississippi River.* Winnipeg: University of Manitoba Department of Botany.

Moyle

(18) Moyle, John B. 1944. Wild rice in Minnesota. *Journal of Wildlife Management* 8: 177 184.

This study indicates survey and examination of wild rice growth during the growing seasons of 1940, 1941, and 1942. In this article, Moyle provides background information on wild rice in general, ecology of wild rice, harvesting history in Minnesota, harvest methods, wild rice crop fluctuations and factors associated with crop failure, and ideal conditions for wild rice growth. Moyle indicates that the ideal conditions for successful wild rice propagation include the following.

1. Clear water, 1 to 3 feet deep, with total alkalinity greater than 40 ppm and sulfate (SO_4) concentration less than 10 ppm;
2. Organic soil 6 inches or more in depth, preferably with some calcareous material such as snail shells;
3. Some movement of water through the area;
4. Fluctuation of water level less than 6 inches throughout the growing season; and
5. Absence of carp.

Moyle indicates the following in his study:

In Minnesota, the chemical nature of the water seems to be the principal factor affecting the natural distribution of wild rice. This crop tolerates the entire carbonate (total alkalinity) range of Minnesota waters (5 to 250 ppm), but is intolerant of sulphates. No large stands of rice occur in water having a SO_4 content greater than 10 ppm, and rice generally is absent from water with more than 50 ppm. Best growth is made in carbonate waters having total alkalinity greater than 40 ppm. Most Minnesota wild rice stands are on mucky soils over gravel and sand. The crop grows best in lakes having some water moving through and often is lacking from stagnant lakes and pools, especially bog lakes with dark brown water. It is frequent along streams and at lake inlets and outlets.

Additionally, the study indicates that based on data collected for over 20 years at Nett Lake (Koochiching County) and the Platte and Sullivan lakes (Morrison County) wild rice stands, “the harvest during any four years is likely to fail once and to produce one bumper and two fair crops. Failure results mainly from high water during June and July.”

The journal article does not clearly explain what methods Moyle used as the basis for some his conclusions, but cited other sources of information. There is some discussion on a wild rice survey for stand size in Minnesota, particularly in “principal stands of more than 500 acres each.” Moyle indicates the principal stands are located in Nett Lake, Koochiching County; Upper and Lower Rice lakes, Clearwater County; Star Lake, Otter Tail County; Lake Minnewawa, Aitkin County; and Big Rice Lake, Cass County. During wild rice surveys conducted between 1940 and 1942, wild rice in stands of five acres or more were estimated at over 15,000 acres statewide.

Moyle, John B. 1956. Relationships between water chemistry of Minnesota surface waters and wildlife management. Journal of Wildlife Management 30(3): 303-320.

This study looked at the regional water chemistry of Minnesota by conducting 1,546 analyses on lakes across the state. The chemical constituents considered in the analyses included total alkalinity, sulfate, chloride, total phosphorus, and total nitrogen. The study provides figures showing the general trends in the state for where certain concentrations of each of the chemical constituents is likely to be found. The concentration of sulfates increases in Minnesota from northeast to southwest "and is highest where the water lie in gray drift which is underlain by Cretaceous formations and where evaporation from open water surfaces is greatest." The study, completed in 1956, concluded that "concentrations of sulfate ion greater than 400 ppm are rare in Minnesota waters, and there is no evidence that concentrations found in fish lakes are injurious to fish." Moyle hypothesizes that "the cause-and-effect relationship between sulphates and the distribution of plants is not known, but may be related to sulphur demands in plant nutrition, osmotic pressure of the water solution, or the toxicity of magnesium usually associated with sulphates."

The study indicates that "there is some evidence that in fertile hard-water lakes with well-developed thermocline, sulphate concentrations may be lower below than above the thermocline. This suggests that under anaerobic conditions below the thermocline sulphates may be reduced to hydrogen sulphide or elemental sulphur."

(19) Moyle, John B. 1967. Wild rice – some notes, comments and problems. *Special Publication No. 7.* St. Paul: Minnesota Department of Conservation, Division of Game and Fish. Revised July 3, 1969.

This document discusses the ecology of wild rice and environmental conditions to establish wild rice paddies. Moyle indicates an absence of wild rice in waters with high alkalinity or sulfate concentrations.

> *In Minnesota, wild rice is not found in waters high in alkali or sulfate salts. There are no large stands in waters in which the concentration of sulfate ion exceeds 10 ppm. Waters with concentrations greater than this are found mostly in that part of the state that was originally prairie – in the southwest and extreme west. Plantings in such waters have failed to produce stands. Even though there may be some growth the first season such stands have not perpetuated themselves….The physiology of this relationship is unknown but it may be due to magnesium toxicity, since magnesium is commonly associated with sulfates, or may be due to the breakdown of sulfates to hydrogen sulfide in the submerged soils.*
> *In Minnesota the fairly sharp separation between carbonate waters in which wild rice grows well, and the sulfate waters is mostly a matter of geology and soils. Rainfall and evaporation are also concerned and sulfate waters are characteristic of semi-arid and arid regions, such as those that are characterized by prairie grasses.*

The document further explains the wild rice seeding and harvesting processes, the history of harvesting, including Native American methods and political ownership history of wild rice stands, and crop yields and sale prices at the time of publication. The document references Moyle's 1944 study in the bibliography.

(20) Moyle, John B. and Paul Krueger. 1969. Wild rice in Minnesota. *Information Leaflet* 5. St. Paul: Minnesota Department of Conservation, Division of Game and Fish. June 26, 1969.

This document provides a historical discussion of wild rice including growth, harvest, distribution, seeding, cultivation and diseases. On page 3 of the document, Moyle provides a discussion on good natural conditions for planting and growing wild rice. The text references sulfate levels and expands slightly on growing criteria and geographic extent of wild rice in Minnesota. His conclusions in this document are the same as in previous documents as described in the following excerpt.

> *Wild rice has marked preference for the quality of water in which it grows and is not found in prairie waters which have appreciable amounts of sulfate or "alkali" salts. In Minnesota the range is mostly limited to waters with concentration of sulfate or "alkali" salts lower than 10 ppm of sulfate ion. Plantings of wild rice seed in prairie waters with higher concentrations of sulfates have generally failed to establish permanent stands.*

The document also provides a list of principal stands were used for harvesting wild rice. The stands listed in Itasca County include:

ITASCA COUNTY

Bass Lake and Bass Creek and Bass Lake to the Mississippi River	T. 55-56, R. 26
*Big Fork River to Dora Lake	T. 147-148-149, R. 26-27
Blackwater and Cut-Off lakes	T. 55, R. 26, S. 8-9-10-16-17
*Bowstring Lake	T. 146-147, R. 25-26
*Bowstring River	T. 147-148, R. 26
Decker Lake	T. 148, R. 29
Dixon Lake	T. 147-148, R. 27-28-29, S. 24-25-36-30-31-1-6-1-12-6-7
*Dora Lake	T. 149, R. 27, S. 1-12-13-14
Dunbar Lake	T. 148-149, R. 27, S. 8-9-16
Gunnie Sack Lake	T. 59, R. 24, S. 9
Mississippi River	T. 55, R. 26-27
Otter Lake	T. 148, R. 29, S. 13-14
*Rice Lake	T. 148-149, R. 27, S. 1-2-35-36
Rice Lake	T. 59, R. 24, S. 8-9
Rice River and Bog all south of Bigfork	T. 60-61, R. 26, S. 34-5-6-8-17-21-25-26-27
*Squaw Lake	T. 148-149, R. 27
Shoal Lake	T. 56, R. 25-26, S. 25-29-30-31
Two Route Lake	T. 55, R. 27, S. 12-13

*NOTE (as provided Moyle's text):

> *The asterisk (*) indicates the larger and more available stands which are usually open to harvesting by both whites and Indians. The other stands are small,*

inaccessible or have harvesting restricted to Indians and local residents only. The size and density of any stand varies from year to year, as does the quality of the rice.

Nelson

(21) Nelson, Ronald N. and Dahl, Reynold P. 1986. The Wild Rice Industry: Economic Analysis of Rapid Growth and Implications for Minnesota.

This report provided research and comparison of wild rice agriculture, harvest, production and yields between California and Minnesota. The report was related to the economic factors of producing wild rice in California and Minnesota and how that would influence the market for wild rice growers in Minnesota. It did not discuss growing factors or water chemistry issues, such as sulfate concentrations.

Oelke

(22) Oelke, E.A. and W.A. Brun. 1973. Paddy production of wild rice. *Agronomy Factsheet* No. 20. St. Paul: University of Minnesota Agricultural Extension Service.

This factsheet provides basic information on how to grow wild rice within paddies. It does not discuss impacts from sulfate or other environmental factors.

(23) Oelke, E.A., W.A. Elliot, M.F. Kernkamp, and D.M. Noetzel. 1973. *Commercial Production of Wild Rice.* St. Paul: University of Minnesota Agricultural Extension Service.

As the title suggests, this report, or factsheet, discusses how to commercially grow wild rice. It discusses factors related to growing wild rice including site selection, seed bed preparation, fertilizer, seed handling, water management, tilling, weed management and pests. It is mentioned on page 4 that "water quality is important. Natural stands usually grow where water has 40-200 ppm alkalinity, a sulfate ion concentration under 10 ppm, and a 6.8-8.8 pH." There are no sources of information cited for this document.

(24) Oelke, Ervin A., J. Grava, D. Noetzel, D. Barron, J. Percich, C. Schertz, J. Strait, and R. Stucker. 1982. *Wild Rice Production in Minnesota.* Extension Bulletin 464. St. Paul: University of Minnesota Agriculture Extension Service.

This study provides general discussion on wild rice biology and history. It discusses varieties of wild rice, methods of seeding, flooded soils, nutrient uptake, fertilization, and water quality. The flooded soils discussion addresses the chemical process that occurs when oxygen is depleted from flooded soils. "The disappearance of oxygen from the soils starts a sequence of reactions involving several compounds. These reactions are linked closely to biological changes taking place in the flooded soil." The reduction of oxidized compounds in the soil takes place in the following order: oxygen, nitrate, manganese, iron, sulfate, and carbon dioxide. If reduction becomes intense enough, sulfate is reduced to sulfide, which is toxic to plants.

A discussion of water quality is found on page 21 of the report. It briefly mentions previous studies completed regarding the potential effects of sulfate on wild rice.

Concern about possible detrimental effects of sulfate in the water is based on earlier observations that no large stands of wild rice occur in Minnesota where sulfate concentrations of surface waters exceed 10 ppm. Sulfate levels commonly found in Minnesota waters do not injure wild rice. Waters in wild rice fields along the Clearwater River range from 22 to 390 ppm sulfate. Most river and lake waters in other areas contain less than 10 ppm sulfate. Wild rice has been grown satisfactorily in experiments at sulfate concentrations of up to 250 ppm.

(25) Oelke, E. A., T. M. Teynor, P. R. Carter, J. A. Percich, D. M. Noetzel, P. R. Bloom, R. A. Porter, C. E. Schertz, J. J. Boedicker, and E. I. Fuller. 1997. Wild rice. In *Alternative Field Crops Manual.* Madison: University of Wisconsin Cooperative Extension Service; St: Paul: University of Minnesota Center for Alternative Plant & Animal Products and the Minnesota Extension Service.

This document discusses wild rice as a field crop, including a discussion on water quality. It states that naturally occurring wild rice is typically found in waters with 10 mg/L or less of sulfate but acknowledges that research has found that wild rice can satisfactorily grow in waters with up to 250 mg/L of sulfate (page 5). The majority of this document provides specific information on wild rice site selection and preparation and factors for growing a successful crop.

Peden

(26) Peden, Donald G. 1982. Factors associated with growth of wild rice in northern Saskatchewan. Arctic 35:307-311.

This was a field study of 17 rice stands in northern Saskatchewan, which looked at sediment chemistry parameters and their influence on wild rice. The study determined that sediment parameter may be useful in identifying potential wild rice planting sites. It concluded that panicle development was primarily related to available P, pH, and concentrations of Na, Ca, Zn, soluble K, Cu, Mn, SO_4, Cl, and Fe in sediment. It is also related to water and substrate depths. The study indicated that chemical changes in the sediment may have caused decreased production of wild rice.

Pillsbury

(27) Pillsbury, Robert W. and Melissa A. McGuire. 2009. Factors affecting the distribution of wild rice (Zizania palustris) and the associated macrophyte community. *Wetlands* 29:724-734.

This document was the abstract only, which indicated that the study examined watershed factors influencing wild rice in lakes and wetlands. The study found that decreases in wild rice plants/distribution may be related to increased residential development within the watershed as well as increased ammonia (from fertilizers), pH and depth. The study did not analyze sulfate.

Rogosin

(28) Rogosin, Alfred. 1954. *An Ecological Life History of Wild Rice.* St. Paul: Minnesota Department of Conservation, Division of Fish and Wildlife.

This paper provides a description of the life history of wild rice including a description of the plant; description of the roots, stem, leaf and reproductive parts; geographic distribution; geologic history and genetic variation. The paper also provides a description of habitat conditions required by wild rice including that wild rice favors mucky sediments and that the best wild rice crops have been observed to occur during low precipitation years with receding water levels in lakes.

The paper also provides a description of water chemistry parameters required by wild rice stating that wild rice is found in "hard carbonate" lakes in Minnesota that have water quality parameters of alkalinity from 40-200 mg/L; sulfate levels from 0-10 mg/L; total dissolved solids of 140-300 mg/L; and pH from 8.0-8.8. Additionally, it is said that no species of zizania (wild rice) are listed for waters having "Alkali or sulfate" water quality. Alkali waters have total alkalinity from 100-225 mg/L; sulfate levels above 50 mg/L usually above 125 mg/L; total dissolved solids above 400 mg/L; and pH from 8.4-9.2. The source for the water quality information referenced in the paper is Moyle, 1945. The paper goes on to list the range of water quality parameters for wild rice from Minnesota waters and states that sulfate range from 3.0 – 282 mg/L with a median of 21.2 mg/L.

Other water quality parameters discussed included salinity and oxygen. A description of sediment conditions preferred by wild rice was provided, concluding that the best conditions for wild rice are soft alluvial sediments covered with one to four feet of water with no greater than 18 to 20 inches of annual water level variation. The paper also provided a description of plants that compete with wild rice for habitat conditions; referencing several Moyle studies for the information. The paper includes additional discussion of the use of wild rice for food by waterfowl. It is agreed to be an important food source by several studies, but one study found that it was the ninth most consumed seed plant based on the examination of stomach contents from 8,000 waterfowl.

(29) Rogosin, Alfred. 1958. Experimental growth of wild rice in relation to water levels, seeding densities, and fertilizer application. *The Minnesota Academy of Science Proceedings* Vols. XXV-XXVI, 1957-1958.

Investigative study targeting the effects of lake water levels on wild rice that was conducted by growing wild rice in wooden boxes filled with lake sediment. Boxes were placed within the lake to ensure the wild rice plants grew in natural lake waters but also allowed water levels within the boxes to be controlled during the experiment. Water level variables included:

- Constant vs. variable water levels: 2 ft and 4 ft used as constant levels.
- Direction of water level change: increasing vs. decreasing.
- Life stage during water level change: pre floating leaf vs. floating leaf
- Amount of water level change: 6 inches vs. 12 inches.
- Rate of water level change: 2 days vs. 7 days to achieve change.

The study results found that the rate of plant development (defined as progression from one growth stage to another) was inversely related to depth of water in which the plants grew. For example, growth of the plants in the 2 ft depth was accelerated as water levels decreased. Additionally, plants subject to a decrease in water levels during the early stage developed faster than those plants experiencing the same conditions at later stages of development. Along these same lines, an increase in water depth seemed to retard the growth of plants. Statistical analysis of the results were either not reported or not preformed.

Additionally, the study examined the effects of fertilization and found that in general fertilized plants consistently had better growth performance than unfertilized plants. The study also found that increased seeding density tended to increase total production of wild rice when the production values were converted to a per-acre basis.

Stewart

(30) Stewart, J.M. 1975(?). A Review of the Effects of Sulfate Ion Concentration on Wild Rice Distribution. Winnipeg: University of Manitoba, Department of Botany.

The purpose of this study was to look at the reasonableness of the current sulfate limit for wild rice (10 mg/L) as it pertained to the Minnesota Power NPDES permit for the Clay Boswell Steam Electric Station. The study relied on literature review to conclude that (1) "the 10 ppm sulfate water quality standard, with respect to waters used in the production of wild rice, is unrealistic;" (2) "Sulfur in the form of sulfate is an essential nutrient for all plants;" and (3) "Sulfate, as an essential nutrient, never acts alone."

The study recommended that "consideration should be given to the revision or deletion of the water quality standard pertaining to sulfate" and further recommended that the Minnesota Power NPDES permit, Number MN 0001007 "should be revised to permit a sulfate concentration in the receiving water at the edge of the mixing zone of at least 200 ppm." This study provided a number of the studies that were reviewed as support evidence for this study's recommendation. The literature was included as appendices to the document, included studies by Moyle and Krueger, 1964; Dore, 1969; and Oelke and Brun, 1969, among others.

Possible additional reference to review:

- Dore, William G. 1969. Wild rice. Canada Department of Agriculture Publication 1393. Ottawa.

(31) Thomas, A.G. and J.M. Stewart. 1969. The effect of different water depths on the growth of wild rice. *Canadian Journal of Botany* 47:1525-1531.

This study examined various plant response variables (plant height, dry weight, etc.) relative to different water depths. The study found that the plant was most vulnerable during the submersed leaf stage of growth (stage 2 of three stages).The study attributed the decline of wild rice in Ontario to either excessively low or high water levels during the critical submersed and floating leaf stages. The study did not analyze water chemistry or the effects of sulfate.

U.S. Department of Agriculture

(32) U.S. Department of Agriculture, Soil Conservation Service. 1973. Wild rice paddy development. *Irrigation System, Surface, and Subsurface* Standard Section IV-445A.

This document was similar to Cullen, 1973 described previously. It focuses on cultivated wild rice. The document provides a list of standards for developing wild rice paddies for commercial production. It discusses water elevations, irrigation, seepage and waste water disposal for cultivated wild rice paddies.

Vennum

(33) Vennum, Jr., Thomas. 1988. *Wild Rice and the Ojibway People.* St. Paul: Minnesota Historical Society Press.

This document included only a one page excerpt, which referenced wild rice does not grow in waters with sulfate concentrations greater than 50 ppm (Moyle, 1944).

Wilcox

(34) Wilcox, Douglas A. and James E. Meeker. Disturbance effects on aquatic vegetation in regulated and unregulated lakes in northern Minnesota. *Canadian Journal of Botany* 69:1542-1551.

This study compared the influence of water level fluctuations on vegetation communities in regulated (Rainy Lake and Namakan Lake) versus unregulated lakes (Lac La Croix). It determined that lakes with regulated water levels has either too little or too much disturbance from water levels which lead to reduced plant community diversity. Wild rice "was conspicuously absent in samples form both Namakan Lake and Lac La Croix. In Lac La Croix, however, viable stands of wild rice were observed in wetlands adjacent to those sampled, and the species seems to be locally abundant elsewhere in the lake."

Winchell

(35) Winchell, Elizabeth H. and Dahl, Reynold P. 1984. Wild Rice Production, Prices, and Marketing. Agricultural Experiment Station, University of Minnesota.

The main purpose of this study was to complete an economic analysis of the wild rice industry as an initial step in providing a guide for future development as an important industry. It examined lake wild rice production throughout Minnesota and Canada, and compared differences in wild rice harvesting regulations. It also provided a discussion of wild rice marketing techniques.

Zhou

(36) Zhou, Wei, Ping He, Shutian Li, and Bao Lin. 2005. Mineralization of organic sulfur in paddy soils under flooded conditions and its availability to plants. *Geoderma* 125:85-93.

This study analyzes the mineralization of sulfur in flooded rice paddy soils of common white rice in China, and does not look at wild rice. It also does not look at sulfate or the impacts of sulfates on plants, but rather is focused on soils.

Bois Forte

(37) Bois Forte Department of Natural Resources Water Quality Program. March 10, 2001. Sulfate and Sulfide Residuals in Water and Sediment, Sandy River and Pike River. Fall-Winter 2000. Prepared for USX, Minnesota Taconite Plant, Mt. Iron, MN.

U.S. Steel requested services from the Bois Forte Band of Chippewa for the collection and analysis of water and sediment from the Sandy River for sulfate and sulfide content. Samples were collected between October 2000 and January 2001 along a seven mile stretch of the Sandy River from Sandy Lake to its confluence with the Pike River. Additional samples were also collected along the Pike River.

Sulfate results from water range between 55.4 ppm and 432 ppm. The western reach of the Sandy River had sulfate levels at 236.35 $\pm$ 57.32 (ppm $\pm$ 1 S.E.), while the eastern reach was 109.81 $\pm$ 30.45 (ppm $\pm$ 1 S.E.). "Wild rice beds were located in the eastern reach of the Sandy River, but were generally limited in extent and sparse in abundance." The study found that "in general, sulfate concentrations were 66 percent higher in water samples taken in areas with no obvious rice beds," but that "variability measures indicate that these results are not statistically significant."

The study analysis indicated that "substantial decreases in sulfate content in sampled water and sediment within rice beds over concentrations found in areas of the river that do not contain rice plants suggests that sulfate is being sequestered in greater amounts within rice bed areas." Further the study indicates that it "cannot conclude whether water-phase sulfate decline within rice beds is due to uptake by plants, other vegetation or biota, or via enhanced redox conversion of sulfate to sulfide with subsequent removal to the sediments."

University of Minnesota – Duluth

Dewey, B. and J. Pastor. 2009. Effect of Sulfate on the Biomass and Seed Production of Wild Rice. A report to the Fond du Lac Reservation Program. University of Minnesota-Duluth. December 20, 2009.

The UMD study planted wild rice seed from Rice Lake on the Fond du Lac Reservation into 128 five gallon buckets using substrate taken from Rice Lake. The wild rice was allowed to mature for one growing season (summer of 2009) during which time, a solution of sulfate ($Na_2SO_4^{2-}$) was added to each bucket at various SO_4 concentration levels (i.e., 0 mg/L, 10 mg/l, 100 mg/L and 300 mg/L). The sulfate concentrations chosen for this experiment were based on typical drainage waters from taconite mines in Minnesota and the Minnesota Rules sulfate standard of 10 mg/L. There were 32 buckets of wild rice for each of the four concentration levels.

The study concluded that "elevated sulfate concentrations significantly decreased wild rice root and total vegetative plant biomasses by 20% or more compared with biomasses of plants grown under low sulfate concentrations typical of natural waters." The study also found that "seed production of plants grown under elevated sulfate concentrations were on average17 percent lower than from plants grown under sulfate concentrations typical of natural waters." Researcher believe that "the significant decline in root biomass may have resulted in nutrient stress to the plants as they may not have been able to exploit as large a volume of sediment to obtain nutrients." The following table (Table 2) was taken from the study and shows the results of wild rice performance at various sulfate concentration levels. The seed production results were considered not statistically significant due to large variability between plants, but indicated that "plants grown under high sulfate concentrations on average produced 17% fewer seeds than plants grown under sulfate concentrations typical of natural waters."

Table 2. Measured plant response to sulfate treatments, values in parenthesis are +/- 1 standard error.

n= 32 for treatments 0, 100, and 300 mg/l, n=30 for treatment 10 mg/l. Treatment (mg/l SO_4^{-2})	Mean Root Weight (g)	Mean Stem Weight (g)	Total Vegetative Plant Weight (g)	Mean Viable Seed Weight (g)	Mean Total Seeds Produced
0	0.812 (0.050)	1.294 (0.062)	2.105 (0.100)	0.0227 (0.001)	29.12 (1.37)
10	0.778 (0.070)	1.387 (0.091)	2.165 (0.146)	0.0229 (0.001)	29.67 (2.32)
100	0.661 (0.050)	1.168 (0.057)	1.829 (0.090)	0.0225 (0.001)	24.00 (1.23)
300	0.595 (0.050)	1.105 (0.069)	1.701 (0.107)	0.0195 (0.001)	25.03 (1.43)

Source: Dewey, 2009

The experiment for this study initially had difficulty getting started. During the first attempt (spring 2008), a greenhouse was used and the wild rice died before reaching maturity. The second attempt (summer 2008) was outside, which due to weather conditions, resulted in poor plant growth and difficulty reaching maturity. The results of this study are based on experiments conducted in summer of 2009, which included some rice worm damage to seeds, resulting in most seed heads having some empty seeds from worms consuming the seed kernel.

Minntac Wild Rice Tech Memorandum

Montgomery, Watson, Harza (MWH). 2004. Minntac Water Inventory Reduction EIS: Wild Rice Technical Memorandum. Prepared for the Minnesota Pollution Control Agency. September 2004.

A technical memorandum on potential impacts to wild rice was drafted as part of the Minntac EIS. This tech memo describes the current ecological status of wild rice within the potentially affected watershed area and defines the potential impacts to wild rice associated with the Proposed Project and selected project alternatives.

The Minntac project was proposing to discharge process water from its current basin into to watersheds: the Dark River watershed to the west and the Sandy River watershed to the east. It was believed that the introduction of overflow water into these watersheds could potentially impact wild rice production currently occurring in the Sandy River. The tech memo does not discuss the Dark River, because wild rice has not currently been found in that river.

The tech memo cited literature regarding high yields for native wild rice and indicated that "high yield in native wild rice is typically accompanied by rice stem densities totaling at or greater than 60 kernel bearing stems (including tillers) per ½ square meter (or 15 or greater stems per square foot) (Archibold and Weichel, 1985; Oelke, 1991). This information on yield and stem densities were used to assess potential impacts to wild rice production in the Sandy River based on the established set of criteria. The criteria, as listed in Table 3.1 of the tech memo, included water level changes, flow rate, heavy metal concentrations, pH, alkalinity, turbidity, calcium carbonate hardness, TDS, dissolved oxygen, and temperature.

TABLE 3.1
BASELINE CRITERIA FOR ASSESSING IMPACTS TO WILD RICE

Criteria	Representative Literature Sources	Comments
Sustained **water level changes** not to exceed six (6) inches or more around baseline conditions during germination, floating leaf, and panicle/kernel production stages in wild rice plant development; flashy changes in water level to be mitigated during months of June-July.	Oelke et al. (1982); Aiken, S. G. et al. (1988); Persell, J. S. (1992); Pillsbury, R. W. et al. (1998); Pip, E., and J. Stepaniuk (1988)	Wild rice-producing lakes of specific importance in the impact area of influence have average depths of approximately two feet. Relatively small water level decreases in these shallow lakes could cause significant long-term impacts on wild rice production and harvest potential.
Flow rate not to exceed 8-10 cubic feet per second (cfs) above site-specific baseline flow rate during germination, boot stage, and floating-leaf stage of the wild rice plant cycle.	Meeker, J. E. (1993); Meeker, J. E. (1996); Dore, W. G. (1969)	
Heavy metal concentrations in plant tissue or kernels above levels not to exceed levels considered acceptable in grains for human consumption, in lakes, streams, and creeks (see also Table 3-2).	Pip, E. (1993); Lee, P. F. (1996); Pip, E. (1984)	
pH not to be less than 6.0 units or greater than 8.5 units during full cycle of wild rice plants.	Oelke, E. A. (1993); Sparling, D. W., and T. P. Lowe (1998); Lee, P. F. (1985); Dore, W. G. (1969)	
Alkalinity minimum levels not to be less than 40 ppm; **Turbidity** within a range of 0.5-10.0 NTU; **Calcium Carbonate Hardness** within 22-500 mg/L, with temporary allowable exceedance; **TDS** to follow site-specific water quality standards.	MCT, 1986; Persell (1991); Oelke et al. (1982); Moyle, J. B. (1944); Dore, W. G. (1969)	Sources cited applies to Alkalinity and Dissolved Oxygen criteria.
Dissolved oxygen levels of between 8-10 ppm in spring germination (April-June), and during fall turnover; may drop to 2 ppm or less during maturing phase of the rice growth cycle without injury to plants. **Temperature** not to exceed five (5) degrees F change around baseline conditions during germination periods (April-June).		

Table 3.2 of the tech memo provides baseline values and toxic thresholds in wild rice based on reported literature, Lee, and Bennett et al. These metals baselines can depend on the part of the plant and locality of the plant that is analyzed. Sulfate concentrations were listed at 0.3-1.3 percent based on reported literature values, but were not defined for Lee or Bennett et al.

The tech memo discusses sulfate impacts, but indicates that "impacts of excess sulfate on wild rice germination, growth, and kernel yield are not clear." The discussion goes on to cite Moyle and current Minnesota Rule standards, but also cites several studies that indicated that wild rice is not impacted until well beyond the 10 mg/L sulfate concentrations, suggesting that "appropriate" sulfate levels for wild rice growth could be bracketed between 10 mg/L and 250 mg/L. Minntac discharge water is well above those sulfate levels.

The Proposed Project included several alternatives (Alternatives A – G) that were analyzed for potential impacts to wild rice.

- Alternative A (Proposed Action): Siphon and discharge continuously to the Sandy River from the tailings basin to near existing tailings basin seepage points; siphon and discharge continuously to the Dark River from the tailings basin to near existing tailings basin seepage points; or hydraulically-controlled release of discharge between the Sandy and Dark Rivers.
- Alternative B: Alternate discharge points

- o Alternative C: No action; tailings basin discharge would not be permitted.
- o Alternative D: Alternative technologies (i.e., perimeter dike raising, water level reduction through operational use, water level reduction through process water adjustment, west tailing basin expansion)
- o Alternative E: Design alternatives (i.e., siphon placement, Dark Lake effluent)
- o Alternative F: Modified scale or magnitude
- o Alternative G: Incorporate reasonable mitigation measures (i.e., submerged, packed-bed reactor (SPB): pre-discharge biological filtration system to reduce sulfate by 50-60% in tailings basin discharge water)

The tech memo indicated that elevated baseline sulfate levels occur in the Sandy River due to seepage from the Minntac tailings basin. Other constituents that are present exhibit no documented toxic effect on aquatic biota. It was also indicated that "historical evidence of the wild rice presence and subsequent loss within Sandy Lake and Little Sandy Lake provides compelling evidence to support the long-term effect of elevated sulfate residuals on wild rice production."

The tech memo provides other possible rationale for the loss of wild rice in Sandy Lake, including internal eutrophication, which can occur under increased sulfate loading to reducing sediments, leading to the formation of hydrogen sulfide (H_2S). It is suggested that further evaluation of the Sandy River system and its wild rice should be carried out using the Roelofs and Smoudlers et al. eutrophication model.

The tech memo concludes that highly concentrated sulfate water has played a role in the decline of wild rice overtime in the Sandy River, and that other chemical and geophysical factors may have also contributed to the loss. It also states that if Proposed Project mitigation is not successful, "all wild rice will be removed from the system."

SONAR 1997 – MPCA Water Quality Standards

MPCA. 1997. Statement of Need and Reasonableness Excerpts-1997: 1997-1998 Great Lakes Initiative Rules chapter 7050/7052 Procedural Document 9; pages 1; 17-46; 71-78; and 155-169. Minnesota Rules 7050.0185, 7050.0210, 7050.0216, 7050.0224, 7050.0460 and 7050.0470; and Minnesota Rules Chapter 7052. Minnesota Pollution Control Agency – Water Quality Division.

The 1997 SONAR addresses proposed amendments to Minnesota Rules Chapter 7050, and proposed adoption of Minnesota Rules Chapter 7052, which governs quarter quality standards, standard implementation, and nondegradation standards for pollutants in the Lake Superior Basin. The rules were proposed to satisfy MPCA's commitment in a memorandum of agreement (MOA) with the Grand Portage Band of Chippewa to "designate a portion of the Lake Superior shoreline waters of the Grand Portage Indian Reservation as Outstanding Resource Value Waters-Prohibited (ORVW-Prohibited)." The proposed rule was also intended to fulfill MPCA's obligation to promulgate rules that enforce the USEPA's Great Lakes Initiative under Section 118(c)(2) of the federal Clean Water Act (CWA).

The designation of the shoreline waters of Grand Portage Reservation at the time was ORVW-Restricted. An ORVW-Prohibited would prohibit new or expanded discharge of bioaccumulative pollutants from any point or non-point source into an area of Lake Superior as described adjacent to the Grand Portage Reservation. At the time of rulemaking, "zoning laws in effect along that portion of the shoreline and on the offshore islands essentially preclude discharges.” Additionally, there are “only eight landowners other than the Grand Portage Band in the area adjacent to the proposed ORVW-Prohibited zone, and no direct discharges to this portion of Lake Superior.”

As explained in the SONAR, “With adoption of the GLI Guidance, EPA now requires NPDES permits issued pursuant to state-developed NPDES permit programs to meet the GLI requirements. Consequently, the MPCA’s adoption of chapter 7052 is a necessary and integral part of maintaining a comprehensive NPDES program acceptable to EPA and ensuring continuation of the NPDES delegation to the MPCA.”

The SONAR relates to wild rice through the proposed amendments to Minnesota Rules Chapter 7050 that specifically address the importance of the wild rice resource and designation of wild rice waters in the Lake Superior Basin. The SONAR is clear in stating that “any additional water quality standards or criteria for the protection of wild rice would be considered in future rulemaking proceedings on this rule,” and not as part of the 1997 rulemaking process.

Beginning in 1993 during public meetings for the proposed rule amendments to Minnesota Rules Chapter 7050, wild rice protection was raised as an important issue by Fond du Lac and Grand Portage Bands. Subsequent to those meetings, additional information was submitted by Grand Portage Band in response to requests by MPCA. This information included a list of 124 lakes and river segments identified as wild rice waters in the 1854 Ceded Territory. Based on discussions with Fond du Lac and the MDNR, the MPCA proposed 22 lakes and two river segments to be specifically listed and identified as wild rice waters in Minnesota Rules Chapter 7050, which are now listed in 7050.0470, subpart 1 for the Lake Superior Basin and identified by a letter code [WR] to signify they are wild rice waters. The proposed amendments also included adding narrative language to 7050.0224 (Class 4A Waters) on the importance of wild rice.

The SONAR described the need for the proposed amendments based on three reasons:

> *1) they are viewed as initial steps in a broader process intended to provide greater public awareness as to the ecological importance of [wild rice]; 2) they provide further support for the study of the physical, chemical, and biological factors that are needed to support wild rice development; and 3) the proposed wild rice amendments represent an affirmation of the MPCA’s commitment to work in concert with the American Indian Band on environmental issues of mutual concern.*

The SONAR indicates that listing wild rice under 7050.0224; Class 4A Agriculture and Wildlife, acknowledges the importance of continued propagation and maintenance of wild rice as a social and cultural resource, resource to wildlife, and genetic diversity of the wild rice species. Beyond the proposed rule amendments, the SONAR suggests that wild rice can be further protected through public awareness; “incorporation of voluntary BMPs relating to wild rice protection into existing activity-specific guidance documents” by MPCA; and mitigating and minimizing potential project-related impacts through timing of the project around wild rice stages of growth, minimizing water fluctuation, replacing or enhancing wetlands, and other voluntary and regulatory means.

Population Cycles of Wild Rice and Its Control

Walker, Rachel and John Pastor. 2008. *Wild Rice: the Dynamics of Its Population Cycles and the Debate Over Its Control at the Minnesota Legislature*. Dissertation for Graduate School at the University of Minnesota. July 2008.

This thesis is separated into five chapters. The first chapter reviews existing literature on the cultural significance of wild rice to Native American Indians. It provides a summary of that review and compares the differences between the views of the various authors and their methods of research. Walker concludes that "Native voices are still absent from mainstream universities and research, as they are from legislative halls and mainstream culture."

The second chapter explores the delays in nutrient cycling in plant population oscillations. The hypothesis is that "delays in release of nitrogen from decomposing litter, caused by microbial uptake, could produce oscillations in [plant] populations when the delay in the release of nitrogen is long than the characteristic time scale of nitrogen uptake." A model was developed by Walker and Pastor to determine if the approximate four-year oscillation period of native wild rice is affected by decomposition of litter and nitrogen uptake. The "model simulations strongly suggest that the delay in release of nitrogen from microbial immobilization during at least the first year of litter decay can potentially cause plant population oscillations." This implies that the generally observed four-year pattern of native wild rice crop fluctuations of one abundant crop followed by a poor crop, and then two fair crops could be in part due to litter decomposition and nutrient cycling. An abundant crop could create increased litter accumulation, which could inhibit plant growth the following year.

Chapter three examined the effects of wild rice straw on biomass and seed production in Northern Minnesota. This research took the modeling data used in chapter two a step further by physically planting wild rice seed gathered from Fond du Lac Ojibwe Reservation in Carlton County, Minnesota for experiments conducted in tanks at the University of Minnesota-Duluth. The experiment found that:

> *Presence and stage of litter decay had the greatest effect on plant growth, sediment N, plant N uptake, and seed production. After a productive year, litter microbes immobilize a large amount of nitrogen during the initial stages of decomposition and reduce production. In subsequent years, litter microbes begin to mineralize nitrogen and production recovers.*

However, the study also acknowledges the various other factors that could affect the patterns of productivity in annual plants, such as wild rice, besides delays in nutrient availability. For example, water level fluctuations can affect productivity and wild rice health. The study concludes correlation between litter decomposition and "several important plant regeneration characteristics." However, it "does not conclude that oscillations are necessarily from delays in nutrients due to microbial activities in wild rice litter," but suggests that the stage of litter decay may have an effect.

A subsequent experiment tested the hypothesis that "quantity of immobilizing litter and tissue also affect population fluctuations. To test the hypothesis, a two-year experiment was conducted using wild rice seed planted in tanks to measure the effects of each year's shoot and root litter quantity and seed number on the following year's production. Results showed that "Tanks which were productive one year (producing large amounts of immobilizing litter) were less productive the following year. Tanks which were unproductive (producing small amounts of immobilizing litter) were more productive the following year." Walker and Pastor concluded that "wild rice population cycles, therefore, depend on the previous year's litter production. Population dynamics of wild rice result from growth allocation to roots or shoots and N cycling influenced by litter decay." The study indicated that more research was necessary to verify the hypothesis.

Chapter five discusses the legislative history of wild rice and recent legislature activity on the issue of genetically engineered seeds and crops, specifically the potential implications of genetically engineering native wild rice. In 2007, the Minnesota Legislature passed legislation requiring the development of an environmental impact statement in cases where a permit is applied for the release genetically engineered wild rice.

This page left blank intentionally.