November 22, 2017

Administrative Law Judge LauraSue Schlatter
Office of Administrative Hearings
600 North Robert Street
P.O. Box 64620
St. Paul, MN 55164

Re: Comments on Proposed Rule Amendments: Proposed Rules Amending Sulfate Water Quality Standard Applicable to Wild Rice and Identification of Wild Rice Waters
OAH Docket No. 80-9003-34519

Dear Judge Schlatter:

The undersigned organizations share an interest in ensuring that modifications to the Minnesota Pollution Control Agency's ("MPCA") rules regarding the protection of water quality in Minnesota are adopted in a manner that is consistent with law and that all modifications are both needed and reasonable. We have cooperatively engaged experts in a variety of fields to provide comments regarding the MPCA's proposed rule amendments referenced above.

The first document we are submitting was prepared on our behalf by Barr Engineering. It provides a summary of the expert comments submitted. Following that document we submit comments from these highly qualified experts on important issues that you will consider in judging the need and reasonableness of the proposed rules amendments:

- Douglas M Hawkins, Emeritus Professor and former Chair of Applied Statistics, University of Minnesota, Twin Cities
- O'Niell Tedrow, MS; Ph. D. Candidate, Biotechnology Lakehead University; Water Resources Scientist Northeast Technical Services, Inc.
- Douglas J. Fort, Ph.D.; President; Fort Environmental Labs, Inc.
- Michael Bock, PhD; Senior Managing Consultant; Ramboll Environ
- Mike Hansel, PE; Principal Emeritus; Senior Chemical Engineer; Barr Engineering
- Kurt Anderson; Director of Environmental & Land Management; Minnesota Power, an ALLETE company (submitted separately by Kurt Anderson)
- Robin Richards, Principal, Ramboll Environ

[Signatures on following page]

U. S. Steel Corporation Ore Operations

Name: Lawrence Sutherland
Title: General Manager

Mesabi Nugget Delaware, LLC

Name: Mark Lorenz
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ArcelorMittal Minorca Mine Inc.

Name: Jonathan Holmes
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Name: TERRY G. FEDOR, II
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Iron Mining Association

Name: Kelsey Johnson
Title: President

Minnesota Power, an ALLETE Company

Kurt Anderson
Director, Environmental & Land Management

Executive Summary

Expert Comments on behalf of Iron Mining Association

In the Matter of MPCA Proposed Amendment of the Sulfate Water Quality Standard Applicable To Wild Rice and Identification of Wild Rice Waters

OAH Docket NO. 80-9003-34519,

Revisor NO. RD4324A

November, 2017

Introduction

The Iron Mining Association of Minnesota (IMA) retained 6 experts in the fields of statistics, toxicology testing, water quality rulemaking, permitting and compliance to review and comment upon the MPCA's Proposed Permanent Rules Relating to Wild Rice Sulfate Standard and Wild Rice Waters. Each of these experts testified orally at the hearings held by the MPCA. Each of the experts have provided detailed written comments which are attached hereto. This summary provides an overview of those comments, and an overview of the IMA's position on the proposed rules.

Recommendations in support of portions of rule which are needed and reasonable

IMA supports removal the current 10 mg/L sulfate water quality standard. (Proposed amendments to Minn. Rules 7050.0224, Subp. 2, lines7.8-7.10)

- State-of-the-art toxicity testing (Pastor et al and Fort et al) definitively demonstrates that sulfate is not toxic to wild rice at concentrations observed in Minnesota wild rice waters.[1,2]
- State-of-the-art toxicity testing shows a clear dose-response relationship between sulfate and the growth and health of wild rice
- State-of-the-art toxicity testing (Fort et al) determined that the mode of action of sulfate is that of any other salt – exertion of osmotic forces on wild rice disrupts the growth and health of wild rice.
- Therefore, it is reasonable and necessary to remove the current 10 mg/L sulfate water quality standard

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[1] Toxicity Of Sulfate And Chloride To Early Life Stages Of Wild Rice (*Zizania Palustris*), Douglas J. Fort, Michael B. Mathis, Rachel Walker, Lindsey K. Tuominen, Mike Hansel, Scott Hall, Robin Richards, S.R. Grattan, and Kurt Anderson, *Environmental Toxicology and Chemistry*, Vol. 33, No. 12, pp. 2802–2809, 2014 © 2014 SETAC

[2] [2] Effects of sulfate and sulfide on the life cycle of *Zizania palustris* in hydroponic and mesocosm experiments, John Pastor, Brad Dewey, Nathan W. Johnson, Edward B. Swain, Philip Monson, Emily B. Peters, and Amy Myrbo, *Ecological Applications*, 27(1), 2017, pp. 321‑336 © 2016 by the Ecological Society of America

Recommendations to remand portions of rule which are unnecessary and/or unreasonable

IMA recommends elimination of the “protective” sulfide level of 120 µg/L in porewater in Minn. Rules 7050.0224, Subp. 5. A. (Lines 7.17 – 7.21) for the following reasons:

MPCA unreasonably rejected state-of-the-art sulfide toxicity testing which shows that sulfide in the root zone (e.g. in the porewater) is not toxic to wild rice at concentrations observed in Minnesota wild rice waters.   (See Anderson, Fort, Hansel)

State of the art testing

- State-of-the-art toxicity testing (hydroponic testing by Pastor et al and Fort et al) shows that sulfide in the rooting zone is not toxic to wild rice at concentrations observed in Minnesota wild rice waters
- MPCA unreasonably excluded (i.e. made a policy decision) that the research by Fort et al was “deserving less weight in the weighing of multiple lines of evidence. MPCA erred in excluding the research by Fort et al, which unlike the other state-of-the-art toxicity testing was conducted according to Good Laboratory Practices, and followed the recommendations of the MPCA’s own Peer Review Panel. MPCA’s reasons for excluding that research are clearly shown to be specious by Fort and others.
- MPCA unreasonably interpreted its own state-of-the-art testing which showed no wild rice impact from sulfide in the rooting zone (e.g. porewater and sediment). MPCA made the policy decision to include impacts to the “green” portions of the plant (shoots and leaves) which are not exposed to sulfide in wild rice waters, but are instead exposed to oxygenated water where sulfide cannot exist.
- Fort Environmental Laboratories conducted another hydroponics study in November 2017 (unpublished) in response to the MPCA speculations that the water depth was not deep enough in the previous Fort hydroponics study. The study design is substantially the same as that used in the published Fort et al 2017 study, but the water depth was increased from 1 cm to 6 cm. The study was conducted from November 3, 2017 to November 13, 2017. The study was conducted using Good Laboratory Practices, addressed all of the recommendations of the Peer Review Committee, and met all acceptability criteria. Results from the most recent study, as well as previous Fort et al studies confirmed:
    - That sulfide was not toxic to wild rice at concentrations observed in Minnesota wild rice waters;
    - That adequate oxygen was not present at sufficient levels in the test media to support detoxification based on the hypoxic environment, as speculated by the MPCA in their rejection of the 2017 Fort et al study.
    - Rather complexation with Fe is the primary mitigating factor in terms of sulfide toxicity. Thus, the results suggest that detoxification of sulfide in the Fort et al. were also the result of Fe complexation rather than detoxification by the plant itself.
    - The November 2017 study provides even more evidence that MPCA unreasonably rejected the published 2017 Fort et al study and should have given much more weight to its results.

- In the November, 2017 Fort et al study (unpublished), for the most sensitive biological endpoint – emergence (%) – at Day 10, the No Observed Effects Concentration (NOEC) was 1.56 mg/L (or 1,560 µg/L) at 0.8 mg/L iron, the lowest iron concentration tested. The Lowest Observed Effects Concentration (LOEC) at the same day and iron concentration was 3.12 mg/L (or 3,120 µg/L). All other biological endpoints required higher concentrations of sulfide to show effect. Both of these values are more than 10 times higher than the MPCA's proposed "protective" sulfide value, and demonstrate that, when all other variables are controlled, sulfide is not as toxic as MPCA's analysis portends to show.
- At higher concentrations of iron (2.8 mg/L iron), NOEC and LOEC concentrations were even higher – 3.12 and 7.78 mg/L respectively; again much higher than the proposed MPCA's "protective" sulfide value.
- As the Fort et al studies followed GLP and the Peer Review Panel recommendations, they should have been given much more weight by the MPCA.

Statistical Derivation of "protective" sulfide level

MPCA unreasonably derived the "protective" sulfide level using naïve statistical analysis (Hawkins, Bock, Anderson)

- In fact, all of the field data represent "no effect" levels, compared to the state-of-the-art toxicity testing (hydroponic testing). (Anderson)
- Sulfide explains only 7%, of the total deviance in wild rice presence, leaving the remaining 93% unexplained. This means that while porewater sulfide is a statistically significant part of the picture of wild rice presence or absence, it is only a modest part of it. Its contribution pales next to that of other characteristics and variables. Sulfide has a statistically significant separation between water bodies with and without wild rice, but is not particularly effective in differentiating between the two. (Hawkins)
- An examination of the field data shows that there are a great many waterbodies in the MPCA dataset that exhibit porewater sulfide concentrations that exceed the MPCA threshold (>120 µg/l) and also possess healthy stands of wild rice. This finding calls into question the validity of MPCA threshold and suggests problems in how MPCA used the field data to derive a threshold. (Bock)
- The field data used in MPCA's analysis was collected in 2012 (n=83) and 2013 (n=25). Significant flooding was reported in the Duluth region in 2012. This flooding occurred in June, a critical time for the germination of wild rice. MPCA did not discuss the possible important of this flooding on in the 2012 data and the derivation of the sulfide threshold. In fact, more than 75% of the 25 samples with porewater sulfide between 100 µg/l and 150 µg/l were collected in 2012, the samples expected to have the most influence on the MPCA's 120 µg/l threshold. (Bock, Anderson)
- MPCA's first derivation of a sulfide threshold is based on the 'breakpoint' analysis of the field data described on page 69 of the SONAR and on pages 37 and 39 of the Final Technical Support Document (TSD; MPCA 2017). This threshold is based entirely on MPCA's visual interpretation of the plot. In my [Bock's] professional judgement there is no visual evidence for a breakpoint at 120 µg/l and this value represents a visual artefact. The use of professional judgment, either MPCA's or my own, can easily lead to unconscious biases and has a high potential for erroneous conclusions. (Bock)

- When specifically piecewise regression (Seber and Wild, 1989) methods are applied to the MPCA field dataset they indicate (1) if the lake with the highest sulfide is excluded (Bean) the ‘breakpoint’ is more than twice the value identified by MPCA (2) if all water bodies are included the breakpoint is more than 1000x the MPCA value and suggests no sulfide threshold in the field data. More simply put, the true threshold could be substantially higher than 300 µg/l. (Bock)
- MPCA conducted another analysis of the data using ‘change point’ analysis to identify a threshold (SONAR 6E p 69). The results of these analysis show that the single change point identified by MPCA is not unique and in fact does not represent a change point that can be associated with a change in wild rice density. (Bock)
- Change point analysis can also be applied to the presence of wild rice and to the presence of dense stands of wild rice with a stem density of greater than 40 stems per square meter (TSD page 50). These statistical change points are all substantially higher than the MPCA threshold of 120 µg/l, supporting the conclusion that 120 µg/l is below the true threshold. (Bock)
- Typically a dose-response statistical model would be used for this sort of data, such as the relationship shown on pages 119-120 of the TSD for probability of wild rice presence versus pore water sulfide. However, the field data do not fit the requirements of such a model; specifically (1) there no well-defined no-effect level due to high variability at all sulfide concentrations, and (2) sulfate is a nutrient required for plant growth (TSD page 53). Although MPCA does fit the field data to a dose-response curve, the data do not fit the assumptions of the statistical model and therefore any sulfide threshold derived using this method should not be used. (Bock)
- Binary analysis presents an alternative method for analyzing the relationship between wild rice and sulfide that is not affected by the issues that plague the dose-response modeling of the field data. These results indicate that the MPCA threshold of 120 µg/l is too low, and higher thresholds (2-3) are just as protective as the MPCA threshold. Furthermore, there are too few data points in the field data with porewater sulfide values high enough (300 µg/l or higher) to reliably determine a true upper threshold. MPCA unreasonably excludes the alternative threshold of 300 µg/l in TSD Appendix 9. (Bock)
- MPCA failed to account for other statistically significant stressors to wild rice, stressors which affect wild rice presence and density (Anderson, Tedrow, Hansel)
- In summary, going from a cutpoint of 120 to 274 µg/L produces many fewer alarms, and those alarms that are produced are much more likely to indicate real problems with the wild rice. If sulfide is used as an indicator of suitability for wild rice, a higher sulfide cutoff should provide a better use of resources for followup. (Hawkins)
- Based on the weight of evidence, I conclude that the 120 µg/l sulfide threshold proposed by MPCA is overly conservative and the true threshold is at least 2-3 times higher than the MPCA threshold. (Bock)

IMA recommends "protective" sulfate equation based on "protective" sulfide level in Minn. Rules 7050.0224, Subp. 5. B. 1. (Lines 7.22 through 8.17) be remanded as it is neither reasonable nor needed.

- MPCA admits that its equation "has nothing to do with wild rice" and only explores the relationship between porewater sulfate and sulfide (Anderson, Hansel)
- I found a significant conflict in the performance of the equation that indicates that the equation does not provide sound predictions of the relationship between sulfide and sulfate and therefore is an unreasonable standard. Any equation used to derive a sulfate standard must yield higher sulfate standards in a waterbody when higher sulfide thresholds are used. The fact that this is not true for the MBLR equation indicates that the equation is likely to lead to erroneous conclusions and is potentially simply a statistical anomaly. The use of such an equation presents a fundamental flaw in MPCAs approach and should not be used. (Bock)
- The waterbody-specific sulfate standard proposed by MPCA does not differentiate waterbodies hosting wild rice from water bodies that do not. (Hawkins)
- More generally I have been unable to find any function of SO4, TOC and Fe that can differentiate water bodies hosting wild rice from water bodies that do not. Thus neither the overall model, nor any of the terms in it, is statistically significant. (Hawkins)
- There is not statistically significant relationship between sulfate, iron, organic carbon and wild rice presence or density. In fact, the predictive power of the sulfate equation is "is akin to throwing a die and declaring the water body good if the die shows a 1 or 2 and as bad if the die shows a 3, 4, 5 or 6." (Hawkins)
- Contrary to my conclusion that SO4 has no perceptible connection to wild rice, the MPCA document reports quite favorable performance for the proposed water-body-specific sulfate standard. However this performance is against a surrogate endpoint – sulfide being below 120µg/L – and not the actual endpoint of interest – the presence or absence of wild rice. Thus the use of this surrogate endpoint seems questionable, as do the resulting conclusions. (Hawkins)
- In summary, all four analytes show substantial variability over time within the same water body. A snapshot of the chemistry at a given time may produce substantially different values than another time. The steady state assumption is therefore not validated particularly well. (Hawkins)
- SO4, TOC and Fe are statistically significant but imprecise predictors of sulfide. As expected, all three terms in the model are highly statistically significant, as is the overall regression. However, while significant, the regression explains less than half the variability (R2 = 0.491), implying that other factors and random variability are responsible for most of the sulfide variability.

IMA contends that there is insufficient information and too many inconsistencies between the studies to derive protective sulfate and sulfide levels.

MPCA has not, and frankly cannot resolve the inconsistencies between the state-of-the-art toxicology research (Pastor et al and Fort et al) and the outdoor container experiments and field surveys. MPCA has not and cannot defend its statistical development of the proposed "protective" sulfide level and "protective" sulfate equation.

MPCA spent only 5 years, and relied only upon 4 sets of experiments to develop the "protective" sulfide level and "protective" sulfate equation. In contrast, the development of water quality criteria for methylmercury, took 10 years of work (science and review) and for selenium, 19 years. Understanding of cause and effect takes time to allow thoughtful consideration given the importance of protecting humans and fish. (Richards)

The implementation guidance for methylmercury (to generate a total mercury water column concentration for a water body) was issued 9 years after the final fish tissue methylmercury criterion was issued[3]. EPA has not yet finalized the implementation (and monitoring) guidance for selenium fish-tissue; work that began in 2004[4]. It is recognized that the models developed by EPA to go from fish tissue level to water column level are very site-specific and typically data intensive (e.g., multiple years of data needed). (Richards)

Using state-of-the-art methods, EPA has shown more than once that a non-water column criteria can be developed from dose-response (aforementioned fish tissue based criteria) and that the confidence one typically has with laboratory water column data, can be achieved in defining a "toxic amount" in fish tissue. If MPCA followed the longstanding EPA approach to water quality criteria development, the wild rice water quality standard would be based on the chemical causing the direct effect, porewater sulfide. (Richards)

MPCA should take a page from EPA and use guidance to implement the porewater sulfide threshold. Certainly MPCA would have far more flexibility to allow implementation of the porewater sulfide threshold concentration into water column sulfate concentrations to exist as guidance, and not regulation. This would also allow MPCA the nimbleness needed to respond to additional data, evolving understanding the geochemistry of wild rice waters, and improved statistical methods. (Richards)

Yet the field data contains an incredible amount of conflicting information that the MPCA has chosen not to evaluate. For example, the densest natural wild rice stand in the entire MPCA filed study, Lake Monongalia, had sulfide levels up to eleven times higher (1,370 ppb) than the proposed protective standard. This kind of discrepancy begs numerous serious questions about the validity of the MPCA's proposed safe level of 120 ppb sulfide, and Lake Monongalia is not the only waterbody where this is observed. Fifty seven percent (57%) of waterbodies with sulfide above 120 ppb have wild rice present, including some of the densest stands in the state. (Anderson)

It is also striking to note that the MPCA has chosen to exclude commercial paddy rice data they collected, despite the fact commercial wild rice stands have the same species of wild rice, and operators and owners specifically design paddies to optimize wild rice production. These commercial paddies, described in more detail later in this document, unsurprisingly have dense wild rice stem counts. They also have high sulfide levels; eight of the twelve are above the MPCA proposed protective level, with the highest sulfide value over 800 ppb. (Anderson)

[3] EPA. 2010. Guidance for Implementing the January 2001 Methylmercury Water Quality Criteria. Available on-line: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1007BKQ.PDF?Dockey=P1007BKQ.PDF
[4] EPA. 2016. Technical Support for Adopting and Implementing EPA's 2016 Selenium Criterion in Water Quality Standards, Draft. Available on-line: https://www.epa.gov/sites/production/files/2016-10/documents/technical-support-adoption-implementation-selenium.pdf

First, we must strip away the MPCA's unsupportable assumption that wild rice should be present if lily pads are present. Indeed, we must take this a step further; because there are so many factors affecting whether wild rice can grow in a waterbody, we must remove all waterbodies from the analysis which do not have wild rice present. Instead, when we do a simple trend-line analysis, it actually shows an increase in wild rice abundance as sulfide levels increase. We also see that just as in natural lakes and streams, as sulfide increases in commercial paddies, wild rice abundance increases. (Anderson)

MPCA ignored the confounding effects of other wild rice stressors in the field surveys. Focus on specific chemical characteristics of surface waters and associated sediment porewaters of wild rice (WR) areas may currently be non-warranted. Initially, system-wide physical and biological characteristics – specifically, water depth and competing vegetation – of waters containing WR should be the focus, if maintenance or management of that resource for WR production is the overall objective. Multiple examples of each of these influences can be observed occurring independently or, as is sometimes the case, concurrently. (Tedrow)

MPCA's model incorrectly neglects the significant interaction between groundwater, sediment and porewater.

IMA contends that MPCA did not adequately specify implementation methods, particularly laboratory analytical methods.

Ramboll has reached out to over 10 reputable certified (e.g., NELAC) commercial water testing laboratories and none of them either are set-up to run this method or routinely run this method to be confident in the quality of their results at a RL of 10 to 15 ug/L sulfide[5]. One commercial lab who has been a leader in AVS and sulfide analytical method development, Alpha Analytical, noted that colorimetric methods have a high potential for false positives due to naturally colored water.

MPCA needs to fully share all the laboratory quality control data and MDL studies conducted by the state lab to assure that MPCA, existing, new or expanding dischargers, and stakeholders are informed on the reliability and accuracy of Method 4500-$S2^-$ E Sulfide. As of now, neither MPCA nor other parties, can document the reliability and accuracy of a porewater sulfide result that will be key to deriving the enforceable sulfate standard.

As of today, no certified commercial water testing labs are available to conduct this method to a RL of 10 to 15 ug/L sulfide. As MPCA seems to have the most experience with this analytical method, they should engage in public outreach to share their knowledge with commercial labs on reliably and accurately conducting Method 4500-$S2^-$ E Sulfide. (Richards)

MPCA did not fully explain the costs to comply with the proposed rules, and thus does not fulfill its statutory requirements under Minn. Stat. § 14.131 (3) and (4)

The MPCA in the SONAR admits that the costs to reduce sulfate in discharges from municipalities and industry are "prohibitively expensive". For cities, annual costs can exceed $1 million/year. For industry, because flows are generally higher and sulfate concentrations are higher than municipal wastewater, costs are even more "prohibitive". For taconite mines and processing plants, there are multiple

[5] Ramboll personal phone and email communications in August 2017.

discharge points and multiple sources of sulfate, including scrubbers, mines and waste rock piles, tailings basin, as well as rainfall over the vast areas which encompass a taconite mine and plant. (Hansel)

Removing sulfate to reach this unsupported "safe" level of sulfide represent an incredible potential risk to the State's economy. Costs for affected wastewater treatment facilities could be between $20-30 million for a flow of 1 million gallons per day (MGD) wastewater treatment facility. Estimates for larger wastewater treatment facilities could run into the hundreds of millions of dollars. Annual operations and maintenance costs could add millions more. These costs will fundamentally impact the economies and societies of Minnesotans for generations to come, funneling energy and monies away from the real challenges that wild rice faces. (Anderson)

Therefore, the "prohibitively expensive" costs to comply with the proposed rule may provide no additional protection for wild rice. MPCA has not and cannot provide any studies, literature or other evidence that these "prohibitively expensive" costs will have any positive impacts on wild rice. (Hansel)

We respectfully request that the rule be remanded to the MPCA until it does a more complete cost analysis, and can demonstrate that the expenditure of billions of dollars will result in better protection of the use of wild rice for harvest by humans and wild life.

Findings of Expert Witnesses

(By Expert)

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Kurt Anderson

1. Summary

The MPCA has not provided a single documented example of a decline in natural wild rice stands from the impacts of elevated sulfide or sulfate.

The MPCA has not provided information regarding how sulfide, which they propose to be the toxic agent, might actually be impacting wild rice. They have not provided a mechanism regarding how, or when, sulfide affects wild rice above their proposed "protective" level.

The foundation of the proposed standard – the MPCA's proposed protective level of sulfide for wild rice – contains numerous unresolved contradictions, based on the MPCA's own field research and peer-reviewed, published laboratory studies.

1) Fifty-seven percent of the waterbodies with sulfide levels above the MPCA's proposed "safe" level have wild rice present – including some of the densest stands in the entire state.
2) The densest stand of wild rice in a natural lake had sulfide levels eleven times higher than what the MPCA is proposing as "safe".
3) The densest stand of paddy rice – the densest stand observed anywhere in the state-funded study– had sulfide levels over three times higher than what the MPCA is proposing as "safe". The MPCA has chosen to exclude this commercial paddy data.

The MPCA has chosen to exclude data from their own funded laboratory research showing no impact to wild rice in the rooting zone at levels nearly 30 times higher (no effect in the rooting zone at 3,060 ppb sulfide) than their proposed protective level of 120 ppb sulfide.

The MPCA has chosen to discount peer-reviewed, published research that studied the effects of sulfide on wild rice in the rooting zone – a study which was designed based on the MPCA's own hypothesis, and the MPCA's own peer reviewers' recommendations.

Removing sulfate to reach this unsupported "safe" level of sulfide represent an incredible potential risk to the State's economy. Costs for affected wastewater treatment facilities could be between $20-30 million for a flow of 1 million gallons per day (MGD) wastewater treatment facility. Estimates for larger wastewater treatment facilities could run into the hundreds of millions of dollars. Annual operations and maintenance costs could add millions more. These costs will fundamentally impact the economies and societies of Minnesotans for generations to come, funneling energy and monies away from the real challenges that wild rice faces.

The MPCA has not evaluated whether removing sulfate to these levels might actually result in detrimental impacts to the aquatic community, including ion imbalances and nutrient deficiencies due to removal of essential minerals and salts.

Put simply, I feel the proposed sulfide standard is not based on a complete and robust evaluation of the available data and scientific results. Based on the information in the enclosed comment letter and the other information received during the rulemaking process, I urge you to direct the MPCA to withdraw this flawed proposal, and address the significant contradictions and inconsistences discussed herein.

2. Executive Summary

The MPCA has used both field and laboratory (Pastor et al[i], Fort et al[ii]) data to rightly conclude that sulfate in the water column is not directly toxic to wild rice until levels far exceed the existing 10 parts per million (ppm) water quality standard.

Clearly, sulfate did not impact wild rice health or abundance at levels anywhere near the existing 10 ppm sulfate limit in either the laboratory of the field. The MPCA has rightly determined, based on modern research, to not continue implementation of the existing 10 ppm sulfate standard.

While the MPCA has concluded that this "safe" level of sulfide is 120 parts per billion, this proposed protective value – which is the very foundation of the proposed rule -- is far lower than the data would suggest is needed to protect wild rice. There is an abundance of contradictory information to support this assertion in the MPCA's own laboratory and research data, as well as in independent, peer-reviewed, published research conducted by a nationally-accredited laboratory

Certainly, it would also be unreasonable to set a protective level so far below the toxic threshold that it is meaningless to the resource we are seeking to protect. Yet there is much data to suggest this is exactly approach the MPCA has chosen to take: they have selected specific data, some it from questionable test design, to support a protective sulfide level so far below any toxic threshold it is essentially meaningless from an environmental benefit perspective. At the same time, they have chosen to ignore other contradictory lines of evidence that would support a more logical protective level -- with a significantly reduced error rate[iii] -- that would still set a protective level of sulfide far below toxic thresholds.

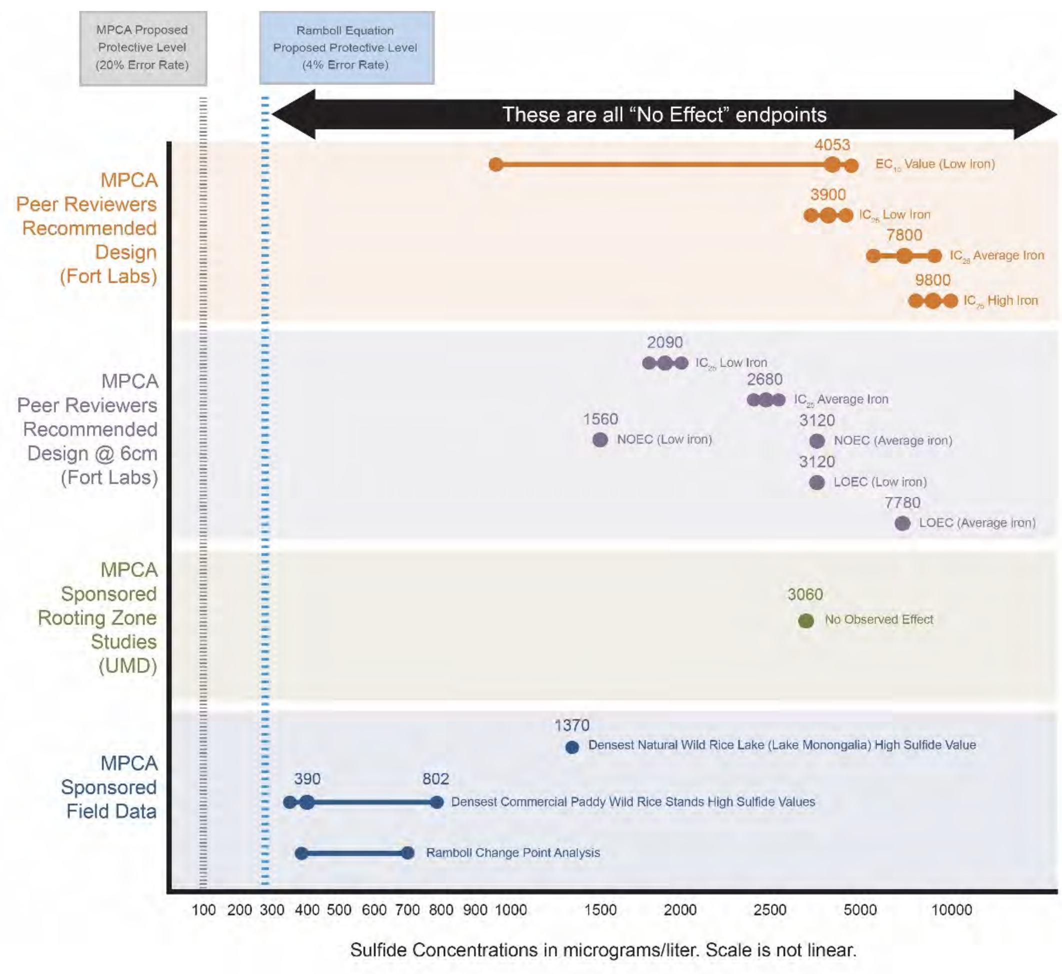
The MPCA's hydroponics testing at the University of Minnesota-Duluth (UMD) found no impact of sulfide at any tested concentration – up to 3,060 ppb – to wild rice in the rooting zone. This high level of sulfide – nearly thirty times higher than the MPCA's proposed protective threshold -- does not represent a toxic threshold. It's a "no impact" level, with wild rice roots in sulfide-enriched water actually growing better than the controls in some cases.[iv]

After these tests failed to show an impact, the MPCA made a policy decision to test the entire wild rice plant, including shoots and leaves. It cannot be overstated how unconventional and contradictory this policy decision was; it violates not only the MPCA theory that sulfide affects wild rice in *the rooting zone*, but also general scientific understanding of where sulfide actually occurs in the natural environment.

Despite numerous and widespread concerns with test design and test performance, the MPCA has chosen to rely on unconventional outdoor container (mesocosm) studies which killed 72-84% of the controls, and the MPCA has failed to acknowledge the serious quality control issues associated with this study. Significantly, the MPCA states the following on page 38 of the TSD: "The EC_{10} values derived from the outdoor mesocosms do not suffer from **any obvious flaw,** although it should be acknowledged that the mesocosms were not perfect mimics of the environment in that porewater sulfide concentrations were probably not in steady state (emphasis added)". It must be noted that any experiment that kills the control organisms over seventy percent of the time can reasonably be considered to contain one or more obvious flaws. Also, a design that completely eliminates the mitigating factors of groundwater upflow in the sediment can reasonable be considered to be an obvious flaw that warrants significant scrutiny. This failure to rigorously examine test results and test quality of these outdoor container studies is yet another indication that the MPCA has not taken a reasonable approach in developing multiple lines of evidence to support their proposed protective sulfide level.

The MPCA has taken a highly questionable approach toward evaluating field research data. They have failed to provide any explanation on a central contradiction to their proposed protective sulfide vale: i.e. why is wild rice growing in dense, thick stands at levels far above (up to ten times higher) than the proposed protective level?

The MPCA has chosen to exclude the information from commercial paddy rice in their evaluation, stating the management practices used in commercial paddies as the basis for this exclusion. Their rationale for this is entirely unclear, however, because the MPCA has yet to demonstrate how or when sulfide might be affecting wild rice.



The conservative nature of laboratory study results is also supported quite well by the field data, which shows the densest stands in the entire state have levels far exceeding the MPCA's proposed protective value.   Again, these are not sparse, marginal stands; they represent the thickest natural wild rice waterbodies (Lake Monongalia) and the thickest wild rice paddies (FS-326).

They have left these anomalies unaddressed, and have seemingly failed to distinguish between correlation and causation. In fact, when one takes a more straightforward view of the field data, even the correlation between increased sulfide and decreased rice does not hold true.

3. History of Existing Water Quality Standard for Sulfate and Wild Rice in Minnesota

Note that not only is wild rice absent or in present in low densities in the generally higher sulfate/sulfide regions of the Northern Glaciated Plains, Lake Agassiz & Aspen Parklands, and the Red River Valley, but it is also largely absent or present in low quantities in much of the (lower sulfate/sulfide) Northern Superior Uplands and Northern Minnesota and Ontario peatlands. Based on this distribution, ecoregion type appears to be a far more significant factor in wild rice distribution than sulfide levels, yet the MPCA has failed to examine these critical components – and the dangers of confusing correlation with causation -- in their proposed rulemaking.

While Moyle indicated he thought a 10 ppm sulfate level was a potential limiting factor in wild rice abundance, he also noted wild rice growing in waters containing up to 282 ppm sulfate (Moyle 1944).

In 1968, E.R. Brooks noted an upper limit of 60 ppm might be closer to an upper sulfate limit, though he noted that trying to determine a limit for sulfate was too singular of a focus; rather, he felt it was the mix of cations and anions that mattered (Brooks, 1968)

Also in 1968, University of Saskatchewan researchers noted that large amounts of sulfate in the soil – up to 1500 ppm -- did not appear to deter wild rice growth in Jackfish Bay (Vicario and Halstead, 1968). They also noted that sulfate levels above 500 ppm seemed to limit plant weight in laboratory experiments however, optimal wild rice growth occurred between 250-500 ppm sulfate.

Other scientists found no impacts to wild rice in the field at sulfate levels of to 170 ppm (Paulishyn and Stewart, 1970). Others recommended an upper threshold of 200 ppm sulfate for paddy rice development (Roaglsky, Clark, and Stewart).

When the MPCA adopted a 10 mg/L sulfate standard to protect wild rice in their water quality rules. Apparently, this was based off of Moyle's fieldwork that was published in 1944 and 1945, and did not account for the additional research conducted by other researchers in the intervening three decades.

4. From a Water Quality Standard to a Wastewater Permit Limit: A Case-Specific Example

Based off the testimony from various experts, as well as field observations and studies, a 40-60 mg/L sulfate limit was eventually adopted at Boswell instead of the 10 ppm standard, and Boswell continues to discharge industrial effluent under those permit limits to this day. With the exception of one other permit in 2013[v], the standard has not been enforced elsewhere at any time.

Fast-forward forty-two years, to 2017 and the proposed rulemaking by the MPCA. The wild rice stands downstream of Boswell are still present and healthy. In the most recent formal field studies[vi], wild rice in the higher sulfate waters downstream of the Boswell NPDES discharge had higher biomass and abundance than the wild rice upstream of the discharge.

Had the MPCA used their proposed 2017 approach back in 1975, the sulfate limit calculated from the MPCA new equation based formula would have been somewhere between 20-25 mg/L, a number based off sediment data collected downstream of Boswell in 2016 by Barr Engineering[vii].

This is exactly the same situation that could unfold across Minnesota of the proposed sulfide-based rulemaking goes forward as currently designed: Extremely high levels of wastewater treatment investment would be needed, with no guarantee or even reasonable chance that environmental benefit for wild rice will actually occur as a result.

5. **Multiple Lines of Evidence: Research on the Effects of Sulfate - Laboratory (or Hydroponics) Research**

The ecotoxicity, or "hydroponics" experiments, were water-only exposures that subjected wild rice seedlings to different levels of sulfate in the water column. Survival and growth of the seedlings were measured, and compared to the levels of sulfate, to determine the "dose response" of wild rice to sulfate. This test sought to isolate the effects of sulfate on wild rice, without the potential interferences of sediment.

These hydroponics tests, conducted by the University of Minnesota-Duluth (UMD), concluded that sulfate levels up to 1,600 mg/L had no statistically significant impact to wild rice seedling germination or growth[viii]. These results were confirmed by an independent ecotoxicity study conducted by Fort Environmental Laboratories (FEL) under Good Laboratory Practice (GLP) protocol, a study which was funded through the Minnesota Chamber of Commerce (Chamber). The FEL study determined the no observed effect concentration (NOEC) of sulfate to wild rice seedlings was 2,500 mg/L on test day 10 and 5,000 mg/L on test day 21. The FEL study was submitted to the MCPA on January 7, 2014, via the Chamber.

These independent tests show roughly the same effect level: sulfate is not toxic to wild rice seedlings until levels are extremely high; nearly twice as high as any recorded sulfate levels in the state's field survey[1].

6. **Multiple Lines of Evidence: Research on the Effects of Sulfate - Mesocosm Research**

Significant seedling mortality is noted in 2012 and 2013. This includes the control exposures, which only had survival ranging from 16-28%. Wild rice seedlings obviously should not have significant mortality if conditions are suitable for wild rice's health and growth; by comparison, the minimum survival control criteria for most chronic effluent ecotoxicity tests is 80%.

7. **Multiple Lines of Evidence: Research on the Effects of Sulfate - Field Research**

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[1] Second Creek in St. Louis County had the highest recorded sulfate level, at 838 mg/L. It also had high wild rice stem density, at ~80 stems/m^2.

. Note that stem density can vary from year to year, due to natural cycling of wild rice population densities.

This data shows that lakes, streams, and cultivated paddies can support moderate to high wild rice densities above 60 stems/m^2 with sulfate levels ranging from just above 10 ppm (Clay Boswell) all the way to 838 ppm (Second Creek).

This field research is among the most compelling information to suggest the existing 10 ppm sulfate standard is neither needed nor necessary to protect wild rice.

8. Multiple Lines of Evidence: Research on the Effects of Sulfide - Laboratory Experiments

However, the attempt to set a water quality standard based on sediment parameters (sulfide) is extremely unusual, and no other similar approaches have been made by other state agencies that this commenter is aware of.

At the MPCA's direction, the UMD researchers again conducted hydroponics testing, this time to determine the toxicity of sulfide on wild rice. Rangefinder tests are often used to set up an approximate range of test concentrations for the actual, definitive exposures.   In this case, the rangefinding tests indicated no significant impact on wild rice seed germination or mesocotyl (see below) growth at levels up to 3,060 µg/L, or 3.06 mg/L.[ix]

Based on the lack of observed toxicity of sulfide, MPCA chose not to conduct definitive testing on the effects of sulfide on seed germination or mesocotyl growth of wild rice. It should be noted that both seeds and mesocotyls can be logically expected to be in the "rooting" zone of wild rice (i.e. the sediment) although mesocotyls could, in some case, also be expected to emerge into the overlaying water.

Surprisingly, these rangefinder tests were conducted by exposing sulfide to the entire seedling, which is in direct contradiction to the MPCA's theory that sulfide was impacting wild rice in the rooting zone, not the rooting zone plus the shoot and leaf zone.   Again, sulfide cannot be present in the water column where oxygen is present, yet the MPCA chose to expose the portions of wild rice in the water column to a toxicant that effectively cannot exist outside the sediment.

Only the shoots and leaves were affected; the parts of the plant in the rooting zone – seeds (germination), roots, and mesocotyls -- were unaffected.

Seedlings exposed all sulfide levels had higher growth roots than the average initial root length. The exposure with 3,060 µg/L sulfide (the highest sulfide concentration) had 8% longer root lengths on average than the controls (2.74 cm compared to 2.55 cm).   The 3,060 µg/l sulfide exposure was the highest concentration tested.

In short, the only measurements -- and subsequently conclusions – that can be derived from the UMD sulfide study are based upon the most ecologically irrelevant exposure pathways – sulfide affecting the shoots and leaves, a place where the scientific consensus is that sulfide cannot exist.

Results from this well-controlled exposure produced significant amounts of data. Most notably, the lowest observed impact for any exposure was an impact to emergence at levels of 1,560 µg/L sulfide, which occurred at the lowest iron concentration (0.8 mg/L) at test day 10. It is important to note that this impact was only noted at test day 10; no impact was observed at the 1,560 µg/L level on test day 21. On Test day 21, the lowest observed adverse effect concentration was 3,100 µg/L at this very low iron level. However, even the most conservative, low-iron, water-only, and temporary (again, no effect was noted at this concentration after 21-days) ”no effect” level of 1,560 µg/L sulfide is more than ten times higher than the MPCA's current proposed protective value of 120 µg/L.

The research also confirmed the MPCA's hypothesis regarding the role of iron. As iron concentrations increased, levels of the free, toxic form of sulfide decreased. As would be expected, toxicity to wild rice seedlings also subsequently decreased. At levels of 2.8 and 10.8 mg/L iron, toxicity was not observed until sulfide reached 7,800 µg/L.

Indeed, sulfide levels in the rooting zone were maintained at the correct dosages in the Fort test design throughout the test duration. The empirical analytical data plainly and directly conflicts with the MPCA's statement, above. Sulfide was present at constant levels, in the rooting zone, throughout the Fort exposure at the desired levels. It was never detoxified; it simply wasn't nearly as toxic when it couldn't attack the green parts of the wild rice plant.

These paradoxical, unproven statements and positions represent a critical departure in the MPCA's approach toward the rulemaking process. Disregarding rigorously designed, peer reviewed research -- refined from the original design, based on the MPCA's own peer reviewers' recommendations -- for unsupported, unproven reasons is highly concerning.

9. Multiple Lines of Evidence: Research on the Effects of <u>Sulfide -</u> Field Research

Put another way, having sulfate levels above 10 ppm meant there was a <u>higher</u> likelihood of having wild present than if levels were below 10 ppm. Therefore, the MPCA made a logical conclusion that this line of field evidence did not support the existing 10 ppm sulfate standard.

: Eighty-one waterbodies have sulfide levels above 120 ppb, of which a full fifty (62%) have wild rice present.

That last bears repeating - -the average sulfide values in wild rice water is approximately 37% higher than what they are proposing as protective.

This is a major assumption, and again, one would assume the field evidence would show a strong link between lily pad presence and wild rice presence. Yet once again, we would be completely wrong; the MCPA's own field data shows that out of the 263 waterbodies, **this assumption fails 115 times.** One hundred and fifteen times, one of the following is true:

This is a very unorthodox approach toward interpreting field data.

Yet the field data contains an incredible amount of conflicting information that the MPCA has chosen not to evaluate. For example, the densest natural wild rice stand in the entire MPCA filed study, Lake Monongalia, had sulfide levels up to eleven times higher (1,370 ppb) than the proposed protective standard. This kind of discrepancy begs numerous serious questions about the validity of the MPCA's proposed safe level of 120 ppb sulfide, and Lake Monongalia is not the only waterbody where this is observed. Fifty seven percent (57%) of waterbodies with sulfide above 120 ppb have wild rice present, including some of the densest stands in the state.

It is also striking to note that the MPCA has chosen to exclude commercial paddy rice data they collected, despite the fact commercial wild rice stands have the same species of wild rice, and operators and owners specifically design paddies to optimize wild rice production. These commercial paddies, described in more detail later in this document, unsurprisingly have dense wild rice stem counts. They also have high sulfide levels; eight of the twelve are above the MPCA proposed protective level, with the highest sulfide value over 800 ppb. Perhaps the most telling point is this: Of the ten commercial paddies with sufficient data, the MPCA's formula predicts there is too much sulfate present in eight of them. If there were permitted discharges to waterbodies such as these – or to Lake Monongalia, or many other waterbodies which produce some of the densest wild rice stands year after year – the MPCA rulemaking could require those dischargers to remove sulfate, with the cost likely in the millions of dollars

10. An Alternative Approach For Field Data Analysis

First, we must strip away the MPCA's unsupportable assumption that wild rice should be present if lily pads are present. Indeed, we must take this a step further; because there are so many factors affecting whether wild rice can grow in a waterbody, we must remove all waterbodies from the analysis which do not have wild rice present.

This leaves us with 54 streams/rivers and 116 lakes, all with varying densities of wild rice, from 0.3 to 154 stems m^2. Forty-seven (47) of these waterbodies do not have stem densities reported. We also see a wide range of sulfide concentrations in this dataset, from 2,080 ppb all the way down to less than the detection limit of 11 ppb.

Instead, when we do a simple trend-line analysis (the green line in the above graph), it actually shows **an increase in wild rice abundance as sulfide levels increase**.

When one plots this data, we see **that just as in natural lakes and streams, as sulfide increases in commercial paddies, wild rice abundance increases**.

This equation results in "protective" sulfate values ranging from 0.36 to 2.45 mg/L. Actual levels of sulfate in these paddies ranges from 0.25 to 279 mg/L.

This regulation, in turn, could not only not help protect wild rice, it could actually cause harm the wild rice population.

11. Conclusion

All we know is that the Agency has proposed a rulemaking with numerous unaddressed contradictions, and they have failed to act in a reasonable manner when evaluating all lines of evidence, and have ultimately failed to show why this regulation, as proposed, is needed.

That other factors affect wild rice does not negate the need to protect wild rice from excess sulfide

Multiple stressors affect wild rice in nature.

The suggestion that sulfide acts independently to affect the presence and absence of wild rice implies there is no interaction between sulfide or any other variable that could potentially influence sulfide presence and bioavailability which is not justified based on historical understanding of sediment sulfide and interactions with other factors described below. I found no attempt to evaluate interactions within the logistic regression. Although this complicates the analyses, it does provide ecological credence in that the ecosystem is not a binary function, it operates in an interactive manner with at least several of the variables considered potentially interacting with each other. Not to at least consider interaction elements in the model, is an over-simplification of the system.

The thought that sulfate, TOC, or Fe didn't have a direct impact on the presence or absence of wild rice is not surprising, as is the thought that their significance in terms of affecting the presence or absence of wild rice is simultaneous. Each of these variables interact directly or indirectly with sulfide to module toxicity. Thus, these statements oversimplify a complicated system in which the toxicity of sulfide which is not in question is modulated by other factors including sulfate, and to a greater extent, TOC and Fe begging the question, why was multiple linear regression not used in the analysis of this data?

The point is, comparison of any means of sulfide toxicity in the environment without consideration of the other confounding variables, Fe and TOC is not justified without further statistical analyses.

Bock

Protective Sulfide level

An examination of the field data shows that there are a great many waterbodies in the MPCA dataset that exhibit porewater sulfide concentrations that exceed the MPCA threshold (>120 µg/l) and also possess healthy stands of wild rice. This finding calls into question the validity of MPCA threshold and suggests problems in how MPCA used the field data to derive a threshold.

Based on my analyses, the conservative sulfide threshold I derived is as protective of wild rice health as the 120 µg/l MPCA standard.

The field data used in MPCA's analysis was collected in 2012 (n=83) and 2013 (n=25). Significant flooding was reported in the Duluth region in 2012. This flooding occurred in June, a critical time for the germination of wild rice. MPCA did not discuss the possible important of this flooding on in the 2012 data and the derivation of the sulfide threshold. In fact, more than 75% of the 25 samples with porewater sulfide between 100 µg/l and 150 µg/l were collected in 2012, the samples expected to have the most influence on the MPCA's 120 µg/l threshold.

MPCA's first derivation of a sulfide threshold is based on the 'breakpoint' analysis of the field data described on page 69 of the SONAR and on pages 37 and 39 of the Final Technical Support Document (TSD; MPCA 2017). This threshold is based entirely on MPCA's visual interpretation of the plot. In my professional judgement there is no visual evidence for a breakpoint at 120 µg/l and this value represents a visual artefact. The use of professional judgment, either MPCA's or my own, can easily lead to unconscious biases and has a high potential for erroneous conclusions.

There are statistical methods that can be used to identify breakpoints, specifically piecewise regression (Seber and Wild, 1989). These methods avoid the biases associated with professional judgment and provide a statistical basis for decision making. When these methods are applied to the MPCA field dataset they indicate (1) if the lake with the highest sulfide is excluded (Bean) the 'breakpoint' is more than twice the value identified by MPCA (2) if all water bodies are included the breakpoint is more than 1000x the MPCA value and suggests no sulfide threshold in the field data.

More simply put, the true threshold could be substantially higher than 300 µg/l.

MPCA conducted another analysis of the data using 'change point' analysis to identify a threshold (SONAR 6E p 69). This method has been described in the peer-reviewed scientific literature (Hawkins 2001, Killick et al. 2016) and does not rely on professional judgement.

The results of these analysis show that the single change point identified by MPCA is not unique and in fact does not represent a change point that can be associated with a change in wild rice density.

Although MPCA limited their change point analysis to stem density, this analysis can also be applied to the presence of wild rice and to the presence of dense stands of wild rice with a stem density of greater than 40 stems per square meter (TSD page 50). The algorithms from Hawkins (2001) were used for this binary change point analysis.

These statistical change points are all substantially higher than the MPCA threshold of 120 µg/l, supporting the conclusion that 120 µg/l is below the true threshold.

Although the methods described above are well founded in statistical theory and provide important information regarding the relationship between sulfide and wild rice health metrics, these methods are not typically used to derive protective thresholds. Typically a dose-response statistical model would be used for this sort of data, such as the relationship shown on pages 119-120 of the TSD for probability of wild rice presence versus pore water sulfide. However, the field data do not fit the requirements of such a model; specifically (1) there no well-defined no-effect level due to high variability at all sulfide concentrations, and (2) sulfate is a nutrient required for plant growth (TSD page 53).

Thus, although MPCA does fit the field data to a dose-response curve, the data do not fit the assumptions of the statistical model and therefore any sulfide threshold derived using this method should not be used.

Binary analysis presents an alternative method for analyzing the relationship between wild rice and sulfide that is not affected by the issues that plague the dose-response modeling of the field data.

Two wild rice health metrics were subjected to binary analysis: (1) the presence of wild rice, and (2) the presence of high density stands of wild rice (>40 stems per square meter). These same metrics were used by MPCA in their analyses (presence/absence of rice, presence absence of high density stands of rice) (SONAR 2 page 69).

Thus, these results indicate that the MPCA threshold of 120 µg/l is too low, and higher thresholds (2-3) are just as protective as the MPCA threshold. Furthermore, there are too few data points in the field data with porewater sulfide values high enough (300 µg/l or higher) to reliably determine a true upper threshold (Table 3).

When I analyzed the field data I found no evidence that increasing the sulfide threshold to values 2-3 times the MPCA value would lead to a discernible decrease in the health of wild rice. There is insufficient data to reliably evaluate higher thresholds.

MPCA unreasonably excludes the alternative threshold of 300 µg/l in TSD Appendix 9.

Based on the weight of evidence, I conclude that the 120 µg/l sulfide threshold proposed by MPCA is overly conservative and the true threshold is at least 2-3 times higher than the MPCA threshold.

Protective sulfate level

I found a significant conflict in the performance of the equation that indicates that the equation does not provide sound predictions of the relationship between sulfide and sulfate and therefore is an unreasonable standard. Specifically, if the sulfide threshold is increased one would expect the sulfate threshold for a given water body to also increase. I found that in a large number of instances, when the sulfide threshold is increased the sulfate threshold decreases. Any equation used to derive a sulfate standard must yield higher sulfate standards in a waterbody when higher sulfide thresholds are used. The fact that this is not true for the MBLR equation indicates that the equation is likely to lead to erroneous conclusions and is potentially simply a statistical anomaly. The use of such an equation presents a fundamental flaw in MPCAs approach and should not be used.

Based on my analysis of the sulfide threshold (Rule 7.20; SONAR part 6E) and sulfate equation (Rule 7.26-8.2; SONAR 6E p75-77), I am recommending the following changes:

1. Reject the sulfide threshold of 120 µg/l.
2. Reject MPCA's equation to predict a waterbody specific sulfate threshold based on TOC, iron, and the sulfide threshold.
3. Explore a more mechanistic approach or evaluate wild rice health in individual water bodies and address those that 1) have lost wild rice relative to historical values or 2) exhibit the qualities expected to support wild rice but that lack stands of wild rice.

Fort

The primary conflict discussed in the testimony provided is the lack of rationale in dismissing a hydroponic study conducted by Fort Environmental Laboratories and published in a well-respected peer-reviewed journal [2].

Since loss of free sulfide increases with increasing Fe addition, we suspect that a significantly proportion of the sulfide was converted to FeS. Therefore, MPCA's statement is based only on the assumption that only detoxification by the rice plant itself resulted in lower toxicity of sulfide, whereas it is the physicochemistry of the hydroponic environment also resulted in chemical reduction in free sulfide due to conversion to FeS which is misleading.

Thus, the present study should be considered in the evaluation of criteria selection and is important in evaluating other factors in the environment that modulate and often mitigate sulfide toxicity to wild rice.

November 2017 study: Results from this study indicate that for the most sensitive endpoint (mesocotyl emergence), exposure of developing wild rice to sulfide at concentrations ≥3.12 mg/L sulfide was toxic based on assessment of NOEC and LOEC values in the presence of 0.8 mg/L Fe. However, exposure of developing wild rice to sulfide at concentrations ≥7.8 mg/L was necessary to significantly reduce emergence in the presence of 2.8 mg Fe/L. Mesocotyl emergence was the most sensitive endpoint in the study, while seed activation, seedling survival, and phytotoxicity were the least sensitive endpoints. Based on measured sulfide concentrations, Fe reduced free sulfide concentrations in the 2.8 mg Fe/L treatment relative to the 0.8 mg Fe/L treatment.

Hansel

1. **Introduction and Overview**

MPCA proposes to delete the current standard of 10 mg/L[2]; this proposal is needed and reasonable and fully supported by the multiple lines of evidence.

The proposed new water quality standard is **unneeded** and **unreasonable** because:

- MPCA, though alerted by their own peer review panel, misconceptualized the hydrogeological conditions under which sulfate is delivered to sediment beds. This flawed conceptual model led to the following issues which pervade their analysis:
    - Unreasonably assuming that chemical diffusion of sulfate from an overlying water column to the sediment porewater is a process favored in these environments; and
    - Unreasonably excluding important controlling variables, such as the concentrations of iron and sulfate in groundwater, from field survey data collection.
- MPCA's model and key hypothesis are incorrect and are not supported out by the multiple lines of evidence;
- In considering the evidence, MPCA improperly weighted the multiple lines of evidence by:
    - Unreasonably excluding or discounting peer-reviewed published science that represents the state of the art in determining toxicity of chemicals to organisms;
    - Unreasonably relying too heavily upon non-peer-reviewed, unpublished science and analyses ;
    - Unreasonably failing to take into account other wild rice stressors, and ascribed all deleterious effects on wild rice to sulfide alone.

The MPCA never states (or proves) that the proposed "protective" porewater sulfide and water column sulfate are needed.

MPCA's initial research followed the state-of-the-art toxicity testing performed on aquatic organisms to determine whether individual substances, such as sulfate, are toxic to those organisms.

2. **Sulfate is not toxic to wild rice (at concentrations observed in Minnesota Wild Rice waters)**

Two state-of-the-art scientific studies clearly demonstrate that sulfate is not toxic at concentrations observed in Minnesota wild rice waters. These studies were conducted in a laboratory where physical conditions were tightly controlled (e.g. temperature, light levels, periods of darkness). Chemical parameters of all other compounds were also strictly controlled, so that only sulfate concentrations varied. Biological parameters were also tightly controlled, with no competition from other competitive or invasive species and no disease parasites. Negative controls – where the wild rice is exposed to zero (or near zero) sulfate concentrations was grown under the same conditions as the exposed wild rice.

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[2] Id at proposed MN rules 7050.0224, Subp. 2

One of the two, Fort et al[3], also used a positive control – where wild rice was exposed to a known toxicant, to be sure that the wild rice was not resistant to chemical toxicants. The Fort et al study also followed Good Laboratory Practices[4], an internationally recognized standard "to ensure the generation of high quality and reliable test data".

Dr. Pastor et al conducted a state-of-the-art controlled toxicity test, and concludes:

"Sulfate exposure concentrations of 0, 10, 50, 100, 400, and 1600 mg SO4/L did not affect germination success, mesocotyl lengths, or the masses of the stem plus leaf (if any) and roots (P > 0.10 for each test)."[5]

Because Dr. Pastor et al struggled early on to grow wild rice in the laboratory, the Chamber commissioned Fort Environmental Labs to conduct similar hydroponic toxicity tests. Fort et al concluded:

"In summary, sulfate concentrations below 5000 mg/L did not adversely affect early–life stage wild rice during a 21-d [ay] period, and effects at 5000 mg/L sulfate were attributable to conductivity-related stress rather than sulfate toxicity in 2 of 4 end points."

There is excellent agreement between Dr. Pastor et al and Fort Labs et al that sulfate is not toxic to wild rice at concentrations seen in Minnesota waters. Dr. Myrbo found the highest concentration of sulfate in wild rice waters to be well under either the 1,600 mg/L sulfate found by Dr. Pastor and the 5,000 mg/L found by Fort Labs et al.

The toxic sulfate levels determined by both Pastor et al and Fort et al, using standard toxicological testing, are more than 1,000 times the current standard of 10 mg/L. It is also interesting that the toxic sulfate levels determined by both Pastor et al and Fort et al, using standard toxicological testing, are more than 1,000 times the median sulfate concentration in streams (17 mg/L) and lakes (3 mg/L).[6] Those same levels are more than double the highest level measured by Myrbo et al. – 838 mg/L at Second Creek.[7]

3. Sulfide is not toxic to wild rice (at concentrations observed in Minnesota Wild Rice waters)

The Peer Review Panel had serious concerns about Dr. Pastor's hydroponic study, and recommended that "If these experiments can be repeated, the panel recommends the following approach:

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[3] Toxicity Of Sulfate And Chloride To Early Life Stages Of Wild Rice (*Zizania Palustris*), Douglas J. Fort, Michael B. Mathis, Rachel Walker, Lindsey K. Tuominen, Mike Hansel, Scott Hall, Robin Richards, S.R. Grattan, and Kurt Anderson, Environmental Toxicology and Chemistry, Vol. 33, No. 12, pp. 2802–2809, 2014 © 2014 SETAC

[4] See OECD webpage at: http://www.oecd.org/chemicalsafety/testing/goodlaboratorypracticeglp.htm

[5] Effects of sulfate and sulfide on the life cycle of *Zizania palustris* in hydroponic and mesocosm experiments, John Pastor, Brad Dewey, Nathan W. Johnson, Edward B. Swain, Philip Monson, Emily B. Peters, and Amy Myrbo, *Ecological Applications*, 27(1), 2017, pp. 321‑336 © 2016 by the Ecological Society of America

[6] MPCA Final Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, August 2011, Chapter 1.A. page 7.

[7] Raw data from Myrbo et al "Sulfide generated by sulfate reduction is a primary controller of the occurrence of wild rice (*Zizania palustris*) in shallow aquatic ecosystems, In press, *Journal of Geophysical Research: Biogeosciences*.

- Use of **a split design**, in which there is a root compartment separated from the shoot. This allows **anaerobic conditions in the root zone to be maintained** and exposure of the root (but not shoots) to the experimental sulfide concentrations.
- Use of an **experimental period of 14 or 21 days**, which is standard in ecotoxicology for aquatic macrophytes. Response measurements should be collected at regular intervals.
- To the extent possible, **use of the same biological endpoints** in the laboratory study as used in the outdoor container and field studies. Decisions on biological endpoints for all the field and laboratory studies in turn will feed into the modeling approaches that can be used. This should be part of the conceptual framework and design for the overall Study and will allow better integration of the study components.
- **A larger sample size**. A power analysis should be done to determine the number of replicates and treatment levels needed.
- We anticipate that **a minimum of six exposure concentrations** should be used, with several treatment levels bracketing the current water quality standard.
- **Maintaining the exposure concentrations throughout the experimental period**. This will be easier if roots are separated from shoots."[8] (Emphasis added)

The results of the Fort Labs study found that at Day 10, with no additional iron, emergence of seedlings was most affected by sulfide, but the lowest observed effects concentration (LOEC) was 3.2 mg/L sulfide.

"Increasing Fe concentrations reduced the toxic effects of sulfide to wild rice," with day 10 LOEC for emergence of seedlings rising to 7.8 mg/L sulfide.

MPCA's essential rejection of the Fort et al sulfide hydroponic study is not reasonable. First, Fort Labs followed as nearly as possible the recommendations of the Peer Review Panel. Second, the Fort Labs study followed Good Laboratory practices and was certified as such. Third, the Fort Labs study followed US EPA guidance for conduct of toxicity testing for the purpose of developing water quality criterion and standards.

Interestingly, despite the fundamental flaws in Dr. Pastor's sulfide hydroponic studies, he found similar results for those parts of the plant which are in contact with the sediment:

"Sulfide concentrations of 0, 96, 320, 960, and 2880 μ g/L did **not** affect **germination success of seeds, mesocotyl masses, or mesocotyl lengths** ($P > 0.10$ for each test)."[9] (Emphasis added)

And

[8] Summary Report of the Meeting to Peer Review MPCA's *Draft Analysis of the Wild Rice Sulfate Standard Study* Saint Paul, MN August 13-14, 2014

[9] Id at 1.

"**Root lengths were only weakly depressed with increasing sulfide concentration** (P < 0.10)."[10] (Emphasis added)

Thus, based on the hydroponic tests conducted by Pastor et al and Fort Labs et al, sulfide is not toxic "in the root zone" or "in the sediment" to those parts of the wild rice plant that lives there, at concentrations of 2,800 µg/L to 3,200 µg/L – hundreds of times more than the "protective" level of sulfide proposed by the MPCA – 120 µg/L. These levels are more than 50 times the median concentration determined during the field surveys conducted by Myrbo as well.

Based on these controlled sulfate hydroponic experiments, there is absolutely no scientific support for the proposed "protective" sulfide standard of 120 µg/L sulfide pore water. Nor is there any scientific support for the notion that sulfide is toxic to wild rice at concentrations observed in Minnesota wild rice waters. Therefore, MPCA has not demonstrated the need for or reasonableness of the proposed "protective" sulfide standard of 120 µg/L sulfide in the porewater.

4. MPCA's Conceptual Model and Key Hypothesis do not correspond to natural conditions

MPCA's analysis has yet to address sulfate in groundwater and its likely control of both the concentrations of sulfide in sediment porewater and sulfate in the surface water column.

In stark contrast, MPCA's conceptual model relies on sulfate delivery to the sediment bed from the overlying water column through chemical diffusion; nowhere does MPCA demonstrate that this mechanism is reasonable. The MPCA also neglects the groundwater contributions of dissolved iron.

So, the MPCA's supposition that a tenuous correlation between water column sulfate and porewater sulfide indicates that the "equation works 80% of the time" is problematic. The tenuous correlation found by MPCA may simply reflect two factors that are controlled by the underlying (and unmeasured) influence of groundwater.

Neither MPCA's conceptual model nor key hypothesis is a reasonable depiction of the natural conditions in wild rice waters. They were specifically called into question by the technical peer review panel, who explicitly identified that the field study "requires addressing the full hydrological system (supply by surface water and groundwater)". The conceptual model used by the MPCA is not borne out in the general understanding of the hydrologic cycle, in decades of research on Minnesota lakes and rivers by USGS and other researchers, or by recent research published by the Minnesota DNR.

5. MPCA's Conceptual Model of wild rice waters as "bathtubs" does not reflect natural conditions

Unfortunately, the MPCA treats their dataset as if wild rice waters are essentially "bathtubs" with no interaction between groundwater and surface water, and no interaction between groundwater and sediment and porewater. Thus, MPCA's model ignores the important role of groundwater in bringing nutrients and sulfate into the sediment and porewater. It is unlikely that sulfate from the surface water is the primary source for the formation of sulfide.

Literature demonstrates that groundwater interacts with sediment and wild rice

[10] Id

Thus, MPCA's model is fundamentally flawed, because it unreasonably implicates the water column as the source of sulfate. It ignores the important role of groundwater in bringing nutrients and sulfate into the sediment and porewater.

MPCA argues that because certain waters don't fit the model (e.g. exhibit "false positives"), the model is correct and the waters that don't fit the model (because groundwater inflow to the sediment prevents the formation of sulfide at levels which have the potential to harm wild rice) are "outliers". Indeed, MPCA presents only one measurement to demonstrate that this occurs; a measurement of Second Creek (see Yourd, 2017)[11]. Those measurements showed that porewater sulfide was lower than the "protective" level of 120 µg/L, "porewater sulfide was less than 120 µg/L in each case despite relatively high sulfate concentrations (303 to 838 mg/L; sulfate was not measured for one of the samplings).

In other words, groundwater "upwelling" through the sediment has been observed as a critical component in the growth of wild rice. Yet, despite the measurements of multiple lakes in Wisconsin and multiple streams and lakes in Minnesota, MPCA holds that the model is still "valid" because of the MPCA's and Dr. Pollman's statistical analysis.

The fact is that groundwater provides much of the flow into wild rice waters, carries with it many nutrients, including dissolved sulfate and iron, and controls the chemistry of porewater in riparian environments. MPCA cannot ignore either the flow or, as will be seen below, the chemistry that accompanies the flow.

6. MPCA's key Hypothesis is not supported by the multiple lines of evidence

Thus, it is unlikely that sulfate from the water column is the main source for sulfide formation in the porewater. It is also likely that iron and dissolved carbon are migrating to the porewater, not from dissolution of the sediment (MPCA's primary source), but are being transported to the sediment, porewater, and ultimately, to the surface water body, via the groundwater flow into the wild rice water. MPCA presents no evidence that sulfate from the water column is the only source for conversion to sulfide in the porewater. It merely makes a policy decision, in the form of the hypothesis, that such is the fact.

In short, MPCA's hypothesis remains a "supposition" or "proposed explanation" – one that is not supported by a general understanding of what controls the chemistry of porewater.

7. State-of-the-Art Controlled sulfate & sulfide toxicity experiments

However, MPCA unreasonably ignored research commissioned by the Chamber as well as other literature, giving all considerably less weight in its weighting of the multiple lines of evidence.

MPCA effectively dismisses the very studies which represent the state-of-the art in toxicity testing, and the best controlled experiments. Pastor et al and Fort et al state-of-the-art controlled hydroponic studies clearly demonstrated that sulfate is not toxic to wild rice at concentrations observed in Minnesota wild rice waters.

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[11] G.-H. C. Ng , A. R. Yourd, N.W. Johnson, and A. E. Myrbo. "Modeling hydrologic controls on sulfur processes in sulfate-impacted wetland and stream sediments" 2017. Journal of Geophysical Research: Biogeosciences 10.1002/2017JG003822

Therefore, MPCA unreasonably relied upon the Pastor et al controlled sulfide toxicity tests (hydroponic tests) in, for example, Figure 1-2 of the TSD[12], and elsewhere throughout the SONAR and TSD.

8. Outdoor Container studies were seriously flawed and cannot be reasonably relied upon.

The MPCA unreasonably relied upon the data generated by Dr. Pastor et al in his outdoor container study. There are serious flaws in the outdoor container studies, because of which the MPCA should have not relied as heavily as it did in developing protective sulfide and sulfate levels.

The MPCA does not resolve the discrepancies between the results of the Fort et al controlled sulfate and sulfide toxicity testing, the Pastor et al controlled sulfate and (properly interpreted) sulfide toxicity testing and the uncontrolled outdoor container studies. These are significant as will be seen.

It is important to note that control mortality at these levels (85%) represents a stressed population of wild rice, and the impact from any added stressors are likely to be greatly exaggerated compared to a healthy population of wild rice.

Thus, the outdoor container tests conducted by Pastor et al did not follow US EPA guidance, and should be given considerably less weight.

Given the serious flaws in the outdoor container data and corresponding Peer Review Panel criticisms, the MPCA cannot reasonably rely upon the results to corroborate a "protective" sulfide" or "protective sulfate" level.

MPCA does not reconcile the differences between the "protective" sulfide levels determined from the hydroponic studies and the outdoor container studies.

Thus, MPCA unreasonably rejects the Fort et al sulfide hydroponic studies, misinterprets the Pastor et al sulfide hydroponic studies, and does not reconcile the fact that there is nearly a factor of 10 difference between these studies and the other studies on which the MPCA relies.

9. Field Surveys were seriously confounded

Unlike the state-of-the-art controlled hydroponic studies, the field surveys are entirely uncontrolled. The wild rice growing in the wild rice waters (and non-wild rice waters) surveyed were subject to weather and all of the other stressors which can affect the presence and density of wild rice.

MPCA acknowledges that several of these other stressors are "statistically significant", yet does nothing to separate their effects from the effects of sulfide. Instead, MPCA ascribes all ill effects on wild rice to sulfide and sulfide alone.

MPCA unreasonably used data from non-wild rice waters to determine "protective" levels of sulfide and sulfate

MPCA ignores other stressors of wild rice, several of which the MPCA determined were statistically significant, in determining the sulfide and sulfide alone impacts the growth and density of wild rice

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[12] [12] MPCA Final Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, August 2011, Chapter 1.C. page 34.

MPCA does not prove its hypothesis, in that there is no causal determination that sulfide in the porewater (e.g. the rooting zone) impacts the presence and density of wild rice

MPCA does not resolve the inconsistencies between the results of the hydroponic studies (where only sulfide or sulfate are stressing the wild rice) and the field surveys, where multiple stressors are operating on the wild rice.

10. MPCA did not adequately consider the costs to comply with the proposed rule

The MPCA in the SONAR admits that the costs to reduce sulfate in discharges from municipalities and industry are “prohibitively expensive”.

For cities, annual costs can exceed $1 million/year

For industry, because flows are generally higher and sulfate concentrations are higher than municipal wastewater, costs are even more “prohibitive”. For taconite mines and processing plants, there are multiple discharge points and multiple sources of sulfate, including scrubbers, mines and waste rock piles, tailings basin, as well as rainfall over the vast areas which encompass a taconite mine and plant.

11. Summary

There are fundamental problems with both the underlying evidence and with MPCA’s policy decisions on weighting the relative value of each line of evidence.

First, MPCA’s model is unreasonable in that it paints all wild rice waters as essentially bathtubs, with no interaction between the surface water, sediment and groundwater, when multiple lines of research show that the groundwater may be the source of the very compounds which may influence the formation of sulfide, and its effect upon wild rice.

Second MPCA’s model is unreasonable in that it assumes that all sulfate migrates to the sediment from the water column, and that all dissolved iron and organic carbon in the porewater (root zone) comes from the sediment. Dissolved iron and organic carbon could just as easily migrate from the water column to the sediment and porewater, and from the groundwater to the sediment and porewater.

Second MPCA’s model is unreasonable in that it assumes that all sulfate migrates to the sediment from the water column, and that all dissolved iron and organic carbon in the porewater (root zone) comes from the sediment. Dissolved iron and organic carbon could just as easily migrate from the water column to the sediment and porewater, and from the groundwater to the sediment and porewater. Research has shown that, in fact, groundwater is the more likely source of all of these compounds. MPCA unreasonably ignores the potential contribution of these migrations, and unreasonably relies upon an overly-simplified model to determine the “protective” level of sulfide and sulfate.

Using the standard, hydroponic toxicity tests per US EPA guidance, sulfate is not toxic to wild rice at concentrations well above the concentrations seen in MN wild rice waters. Therefore, the current standard of 10 mg/L sulfate has no scientific validity. The mode of action of sulfate is also now well understood – it, like other salts, exerts osmotic pressure on the plant, and is no more toxic than any other salt. Therefore, there is no need for a “protective” sulfate standard.

Similarly, based on the effects of sulfide on the rooting zone (and those portions of the plant in the sediment and exposed to the porewater), sulfide is not toxic to wild rice at concentrations seen in most Minnesota wild rice waters. While the mode of action is not well understood at this point, it is clear from these experiments, un-confounded by other wild rice stressors, that sulfide is not toxic to wild rice at concentrations seen in Minnesota wild rice waters. Therefore there is no need for a "protective" sulfide standard.

While MPCA conducts a series of statistical analyses to allegedly show that a "protective" sulfide in porewater standard is needed, both the underlying data and the statistical analysis are fraught with errors, and contradicted by the literature. The result is an inconsistent body of evidence, some of which shows that a sulfide in porewater and sulfate in the water column water quality standard may be necessary, and other showing that such standards are neither needed nor reasonable.

For example, the MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in discharges to surface waters will effectively reduce sulfide in the porewater in wild rice waters. Indeed, Berndt et al[13] reach an entirely opposite conclusion.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in the water column will better protect wild rice. None of the controlled hydroponic studies show any evidence for this, nor do the outdoor container studies nor do the field surveys. Again, Berndt et al [14]shows that sulfate in the surface water has little to do with sulfate reduction in the sediment, while groundwater flow provides the bulk of flow as well as sulfate, organic carbon and iron in the sediment.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in the water column will reduce sulfide in the porewater. This was simply not tested in any of the studies, nor in any of the literature cited by the MPCA. Yet the proposed rule explicitly says that this is what needs to happen to comply with the rule. In wild rice waters where the porewater sulfide exceeds the protective level, dischargers of sulfate will need to reduce their discharges of sulfate. Yet there is no evidence that reducing sulfate in discharges will result in significant reductions in water column sulfate, or that reducing sulfate in the water column will reduce sulfide in the porewater. Considering that cities and industries may be required to expend billions of dollars to reduce sulfate in their discharges, through the use of membrane filtration treatment, MPCA should be able to solidly demonstrate, in at least one wild rice water, that reduction in sulfate results in reduction in porewater sulfide. MPCA has not done so, and thus the proposed rules are unreasonable.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfide in the porewater will better protect wild rice.

Therefore, the "prohibitively expensive" costs to comply with the proposed rule may provide no additional protection for wild rice. MPCA has not and cannot provide any studies, literature or other evidence that these "prohibitively expensive" costs will have any positive impacts on wild rice.

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[13] A comparison of results from a hydrologic transport model (HSPF) with distributions of sulfate and mercury in a mine-impacted watershed in northeastern Minnesota, Michael E. Berndt, Wes Rutelonis, Charles P. Regan. Journal of Environmental Management 181 (2016) 74-79

[14] Id

We respectfully request that the current sulfate standard of 10 mg/L[15] be eliminated, as the weight of evidence clearly shows that sulfate is not toxic to wild rice at that concentration or at any other concentration observed in Minnesota wild rice waters.

We respectfully request that the rule be remanded to the MPCA, to address the errors, uncertainties and inconsistencies noted above, particularly the inconsistency that multiple studies show that concentrations of sulfate and sulfide are not toxic to wild rice at concentrations observed in Minnesota wild rice waters, while other studies show that a “protective” concentration of 120 µg/L, and a “protective” concentration of sulfate, which are orders of magnitude smaller than the controlled, state-of-the-art hydroponic test results.

We respectfully request that the rule be remanded to the MPCA until it does a more complete cost analysis, and can demonstrate that the expenditure of billions of dollars will result in better protection of the use of wild rice for harvest by humans and wild life.

We respectfully suggest that MPCA has not met its obligations under the Administrative Procedures Act to demonstrate the need for and reasonableness of the proposed rule, specifically Proposed MN Rules 7050.0224 Subp. 5. A. (Line 7.17 – 7.12), and Proposed MN Rules 7050.0224 Subp. 5. B.1. (Line 7.25 – 8.17)

Hawkins

The analyses led to the conclusions:

1. **The waterbody-specific sulfate standard proposed by MPCA does not differentiate waterbodies hosting wild rice from water bodies that do not.**

   The P value of this test falls far short of statistical significance, confirming the visual impression that the proposed SO4 limit has no connection to the presence or absence of wild rice in the water body.

   In other words, 60% of the water bodies – a majority – would be misdiagnosed by the proposed standard.

   The performance of the proposed sulfate standard for identifying wild rice sites is akin to throwing a die and declaring the water body good if the die shows a 1 or 2 and as bad if the die shows a 3, 4, 5 or 6.

2. **More generally I have been unable to find any function of SO4, TOC and Fe that can differentiate water bodies hosting wild rice from water bodies that do not.**

   Thus neither the overall model, nor any of the terms in it, is statistically significant.

[15] Proposed Permanent Rules Relating to Wild Rice Sulfate Standard and Wild Rice Waters, MPCA per Minnesota Reviser RD4324A, Proposed MN Rules 7050.0224, Subp.2

The conclusion then is that these three predictors are not informative about the presence or absence of wild rice. Any model using them to predict presence or absence of wild rice can be no better than random guessing.

Whether for wild rice presence, or for the abundance of the wild rice, SO4, TOC and Fe do not show any predictive information in the field data.

3. Sulfide is a statistically significant but weak predictor of wild rice presence.

On the other hand, however, sulfide explains only 10.53, or 7%, of the total deviance in wild rice presence, leaving the remaining 132.87, or 93% unexplained.

This means that while porewater sulfide is a statistically significant part of the picture of wild rice presence or absence, it is only a modest part of it. Its contribution pales next to that of other characteristics and variables.

Like the proportion of deviance explained, the AUC paints a picture of sulfide as one fairly small part of the picture: statistically significant but far short of determinative.

Here too, sulfide has a statistically significant separation between water bodies with and without wild rice, but is not particularly effective in differentiating between the two.

4. The MPCA assessment of the proposed sulfate rule's performance is questionable.

Contrary to my conclusion that SO4 has no perceptible connection to wild rice, the MPCA document reports quite favorable performance for the proposed water-body-specific sulfate standard. However this performance is against a surrogate endpoint – sulfide being below 120 µg/L – and not the actual endpoint of interest – the presence or absence of wild rice.

Thus the use of this surrogate endpoint seems questionable, as do the resulting conclusions.

5. All four analytes vary substantially from time to time within the same water body.

At this level, two sulfide readings on the same water body have a 1 in 3 chance of differing by more than 100%, a proportion supported by the actual successive sulfide readings.

In other words, the sulfide level of a water body is an elusive, moving target.

In summary, all four analytes show substantial variability over time within the same water body. A snapshot of the chemistry at a given time may produce substantially different values than another time. The steady state assumption is therefore not validated particularly well.

6. SO4, TOC and Fe are statistically significant but imprecise predictors of sulfide.

As expected, all three terms in the model are highly statistically significant, as is the overall regression. However, while significant, the regression explains less than half the variability (R2 = 0.491), implying that other factors and random variability are responsible for most of the sulfide variability.

There is a statistically significant but not very strong relationship of sulfate, Fe and TOC to sulfide, and

There is a statistically significant but not very strong relationship of sulfide to wild rice.

This chain of relationships falls apart when the intermediate of sulfide is removed and one attempts to predict wild rice directly from sulfate, Fe and TOC. Then the unmodeled random variability in the two relationships overwhelms the modest associations, leading to the lack of significant association between SO4, Fe and TOC and the presence or absence of wild rice.

7. **The proposed sulfide cutoff of 120 µg/L is not well supported and would lead to many false alarms.**

In summary, going from a cutpoint of 120 to 274 µg/L produces many fewer alarms, and those alarms that are produced are much more likely to indicate real problems with the wild rice.

8. **A different approach using sulfide in a linear discriminant analysis incorporates explicit recognition of the implications of false positive and false negatives, and further motivates higher sulfide cutoffs.**

Even the lowest of these numbers is above the 120 µg/L proposed in the MPCA document. These numbers provide further evidence that, if sulfide is used as an indicator of suitability for wild rice, a higher sulfide cutoff should provide a better use of resources for followup.

In summary, the data presented give little reason to believe that changes in the sulfate standard will have any effect on the occurrence or health of wild rice. A standard focused directly on sulfide would incur substantial numbers of false positives (water bodies with high sulfide but abundant wild rice) and false negatives (water bodies with low sulfide but no wild rice). More detailed study of these water bodies would be required diagnose their specific properties and actions needed to enhance wild rice.

Richards

MPCA has not demonstrated the reasonableness of the following:

- The porewater sulfide concentrations impacting wild rice health (SONAR E.2)
- The MBLR sulfate equation (SONAR E.4 and E.5)
- The porewater sulfide analytical method (SONAR E.7)

Very few details were provided in the published paper on the data used, definition of EC0, EC10, or definition of initial conditions. The peer-reviewed article does not contain an EC10 so it should be noted that any EC10 based on these data were not evaluated during the peer-review process for publication. In a meta-analysis performed for MPCA, Pastor calculated an EC10 of 299 µg/L.

The quality of the test design and execution are not considered of the quality typically used for determine chemical toxicity as per Good Laboratory Practices[16]. This is reflected by a variety of things:

[16] EPA Good Laboratory Practices (GLP) available on-line: https://www.epa.gov/compliance/good-laboratory-practices-standard-operating-procedures

- The scatter (huge variability) of the weight change
- The gap in sulfide concentrations between 100 µg/L and 1000 µg/L
- The high variability in the measured sulfide concentrations the implicit lack of control of aqueous sulfide
- The lack of daily sulfide measurements
- Treatment of what is really 3 range-finding tests as definitive tests

It is not clear whether MPCA has generated a different random subset and conducted a sensitivity analyses to determine that this is valid approach; nor is there an evident rationale for not using the entire initial weights. As presented in Attachment 1, an option of using the geomean of the minimally generated sulfide measurements was investigated by Ramboll Environ. It is not appropriate to use a geomean on this type of data, a time-weighted average is more applicable.

The sulfide EC10s for the Pastor data vary by more than a factor of two, ranging from 103 µg/L to 255 µg/L. Given the variability in these EC10s and significant criticisms of the Peer Review Panel (see Section 3.2.2) these the sulfide EC10s, and any other ECs that may be based on the Pastor dataset, should be considered rough estimates and weighted less heavily in the determination of a porewater sulfide protective value then the other lines of evidence.

To reiterate, the MPCA presentation of probability of wild rice presence versus porewater sulfide is flawed as there is not a well-defined no-effect level due to the high variability in porewater sulfide concentrations and the fact that sulfate is a necessary wild rice nutrient (TSD page 53).

The proven and known approach of developing water quality criteria by developing a dose-response curve has not been reasonably demonstrated by MPCA. Their presentation contains errors and these errors undermine the confidence in understanding and defining the relationship between porewater sulfide and wild rice health.

MPCA correctly states that water column sulfate does not have a direct effect on wild rice – there is no dose-response curve for sulfate vs. wild rice survival, growth, or reproduction. MPCA presents sulfate as having an indirect effect of wild rice. MPCA has defined porewater sulfide as a toxicant causing adverse impact to wild rice. However, as discussed previously, there is minimal confidence in the sulfide threshold developed by MPCA and MPCA's presentation of dose-response relationship is flawed.

Without confidence in the dose-response for porewater sulfide, a "toxic amount" is difficult to define for use in assuring that protection of designated use is achieved. If MPCA followed the longstanding EPA approach to water quality criteria development, the wild rice water quality standard would be based on the chemical causing the direct effect, porewater sulfide.

EPA has not attempted to establish water quality criteria based on an indirect cause of the effect. EPA's water quality criteria are based on the direct cause. As discussed earlier, EPA has recommended criteria that are not water-column based i.e., selenium fish tissue, methylmercury fish tissue.

And
OECD Good Laboratory Practices available on-line:
http://www.oecd.org/chemicalsafety/testing/goodlaboratorypracticeglp.htm

MPCA should take a page from EPA and use guidance to implement the porewater sulfide threshold. Certainly MPCA would have far more flexibility to allow implementation of the porewater sulfide threshold concentration into water column sulfate concentrations to exist as guidance, and not regulation. This would also allow MPCA the nimbleness needed to respond to additional data, evolving understanding the geochemistry of wild rice waters, and improved statistical methods.

MPCA neglected to explain the Vermont process and highlight how the process was very different from the MPCA approach for the MBLR sulfate equation. In particular, specific to the implementation of the Vermont nutrient criteria, an integrated approach to implementation is also presented by Vermont[17]. The integrated approach used by Vermont allows for compliance with nutrient criteria to be evaluated by either comparison to nutrient criteria or by comparison to nutrient response variables (e.g., macroinvertebrate community health). This integrated approach is used <u>because of</u> the misclassification rates of 20 to 40%.

An integrated approach that might be considered is the presence and health of the wild rice in the wild rice water body and if the wild rice were present and healthy, then compliance is demonstrated. Given the amount of MPCA MBLR sulfate misclassification rate, an integrated approach is warranted.

MPCA, by adopting into rule the translation of the porewater sulfide to water column sulfate with the development of the MBLR sulfate equation, needs a level of confidence (e.g., far lower level of misclassifications) that is not currently shown. In addition, Vermont, in recognition of their high misclassification rate (similar to MPCA's misclassification rate) for nutrients, is using an integrated approach for implementation while MPCA is not.

USEPA has issued and continues to update guidance on criteria development including the type of data and statistical methods to define the dose-response. The current state of the science is recognition that the direct cause of an aquatic life (or human health) adverse impact (or effect) may not be due to water-column exposure[18]. This is similar to MPCA's finding that water column sulfate has no direct effect on wild rice.

The development of water quality criteria for methylmercury, took 10 years of work (science and review) and for selenium, 19 years. Understanding of cause and effect takes time to allow thoughtful consideration given the importance of protecting humans and fish.

MPCA correctly states that water column sulfate does not have a direct effect on wild rice – there is no dose-response curve for sulfate vs. wild rice survival, growth, or reproduction. MPCA presents sulfate as having an indirect effect of wild rice. MPCA has defined porewater sulfide as a toxicant causing adverse impact to wild rice. However, as discussed previously, there is minimal confidence in the sulfide threshold developed by MPCA and MPCA's presentation of dose-response relationship is flawed.

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[17] Vermont DEC. 2014 rev 2016. Nutrient Criteria for Vermont's Inland Lakes and Wadeable Streams: Technical Support Document. Available on-line: http://dec.vermont.gov/sites/dec/files/wsm/Laws-Regulations-Rules/2016_12_22-Nutrient_criteria_technical_support_document.pdf

[18] USEPA. 2001. Water Quality Criterion for the Protection of Human Health: Methylmercury. EPA-832-R-01-001. Available on-line: https://nepis.epa.gov/Exe/ZyPDF.cgi/20003UU4.PDF?Dockey=20003UU4.PDF
and
USEPA. 2016. Aquatic Life Ambient Water Quality Criterion for Selenium – Freshwater. Available on-line:https://www.epa.gov/sites/production/files/2016-07/documents/aquatic_life_awqc_for_selenium_-_freshwater_2016.pdf

Using state-of-the-art methods, EPA has shown more than once that a non-water column criteria can be developed from dose-response (aforementioned fish tissue based criteria) and that the confidence one typically has with laboratory water column data, can be achieved in defining a “toxic amount” in fish tissue. If MPCA followed the longstanding EPA approach to water quality criteria development, the wild rice water quality standard would be based on the chemical causing the direct effect, porewater sulfide.

However, the implementation of these criteria to water column levels, or translation to a water column concentration, is considered a separate activity and is not part of the EPA’s national recommended criteria. What this means is that while EPA criteria are suitable (and typically encouraged) to be adopted into state water quality standards programs, translation of criterion to water column concentration is not encouraged by EPA to be part of state regulatory water quality standards. It is recognized that the models developed by EPA to go from fish tissue level to water column level are very site-specific and typically data intensive (e.g., multiple years of data needed).

The implementation guidance for methylmercury (to generate a total mercury water column concentration for a water body) was issued 9 years after the final fish tissue methylmercury criterion was issued[19]. EPA has not yet finalized the implementation (and monitoring) guidance for selenium fish-tissue; work that began in 2004[20]. Point being: the amount of data and information needed takes time to generate, validate, and utilize to be able to develop the sound models and recommendations to translate the direct effect (methylmercury in fish tissue or selenium in fish tissue) to water column concentrations (mercury in water column or selenium in water column).

As presented by MPCA, the MBLR sulfate equation (which is a model) is not aligning with porewater sulfide or wild rice health (MPCA uses the term “misclassification”) for an alarming number of waterbodies (TSD, page 48 to 62, 67 to 83; SONAR page 77 to 79) as one considers the regulatory impact on agency decisions and actions.

MPCA should take a page from EPA and use guidance to implement the porewater sulfide threshold. Certainly MPCA would have far more flexibility to allow implementation of the porewater sulfide threshold concentration into water column sulfate concentrations to exist as guidance, and not regulation. This would also allow MPCA the nimbleness needed to respond to additional data, evolving understanding the geochemistry of wild rice waters, and improved statistical methods.

MPCA’s identification of porewater sulfide as the direct cause of an adverse impact on wild rice is similar to EPA’s fish-tissue based criteria. However, EPA has taken the time to generate robust and valid data and methods to translate the fish-tissue criteria to water column chemical concentrations and the translation is adopted as guidance; not a water quality criterion or rule. MPCA, by adopting into rule the translation of the porewater sulfide to water column sulfate with the development of the MBLR sulfate equation, needs a level of confidence (e.g., far lower level of misclassifications) that is not currently shown. In addition, Vermont, in recognition of their high misclassification rate (similar to MPCA’s

[19] EPA. 2010. Guidance for Implementing the January 2001 Methylmercury Water Quality Criteria. Available on-line: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1007BKQ.PDF?Dockey=P1007BKQ.PDF

[20] EPA. 2016. Technical Support for Adopting and Implementing EPA’s 2016 Selenium Criterion in Water Quality Standards, Draft. Available on-line: https://www.epa.gov/sites/production/files/2016-10/documents/technical-support-adoption-implementation-selenium.pdf

misclassification rate) for nutrients, is using an integrated approach for implementation while MPCA is not.

MPCA does list acceptable analytical performance but neglects to identify the required MDL. My opinion is given MPCA's use of a porewater sulfide threshold of 120 µg/L, the MDL should be at least 3 to 5 µg/L and the RL 10 to 15 µg/L to have confidence in using the data to derive an enforceable sulfate standard. The accuracy (bias) statement presented by MPCA is different than that included in Standard Methods. Further, no documentation or data on the development of an acceptable recovery of 80 to 100% (versus 97.6% to 104.2%) is provided by MPCA.

Ramboll has reached out to over 10 reputable certified (e.g., NELAC) commercial water testing laboratories and none of them either are set-up to run this method or routinely run this method to be confident in the quality of their results at a RL of 10 to 15 µg/L sulfide[21]. One commercial lab who has been a leader in AVS and sulfide analytical method development, Alpha Analytical, noted that colorimetric methods have a high potential for false positives due to naturally colored water.

MPCA needs to fully share all the laboratory quality control data and MDL studies conducted by the state lab to assure that MPCA, existing, new or expanding dischargers, and stakeholders are informed on the reliability and accuracy of Method 4500-$S2^-$ E Sulfide. As of now, neither MPCA nor other parties, can document the reliability and accuracy of a porewater sulfide result that will be key to deriving the enforceable sulfate standard.

As of today, no certified commercial water testing labs are available to conduct this method to a RL of 10 to 15 µg/L sulfide. As MPCA seems to have the most experience with this analytical method, they should engage in public outreach to share their knowledge with commercial labs on reliably and accurately conducting Method 4500-$S2^-$ E Sulfide.

Tedrow

1. **SUMMARY**

- Controlling competing vegetation in waters intended for WR production is critical for maintenance of desired WR growth, distribution, abundance, and productivity. Competitive exclusion and potential allelopathic influences from competing vegetation can substantially limit WR health and productivity, with the potential for elimination from the area or water resource.
- Achieving and maintaining an appropriate water depth in WR areas is one of, if not the, more important variables to control for WR plant growth, development, reproduction, and abundance. In the absence of appropriate water depth control, WR plants will be under excessive stress, which may result in decreased health and abundance with subsequent elimination from an area or water resource.
- In general, for prairie potholes, in the absence of water depth control and maintenance of a preferable WR water depth, and the almost ephemeral nature of prairie potholes re: presence /

[21] Ramboll personal phone and email communications in August 2017.

absence of standing water, prairie potholes are unlikely to be acceptable habitat for WR production, regardless of chemical characteristics of overlying water and sediment pore water.

  - Prairie potholes are not generally controlled, or controllable, for WR production. Reference of prairie potholes as poor WR habitat specifically due to chemical characteristics that may be detrimental to (WR) growth is incomplete, and not necessarily defensible if not considering the variable hydrological cycle(s) of any specific pothole.

- Suggesting that water lilies are indicative of acceptable WR habitat is an incomplete statement. In the areas presented here, WR and water lilies do occur in the same general area; however, a distinction between higher density populations of each plant appears evident. Therefore, simply stating that the presence of water lilies is an indicator of acceptable WR habitat is overgeneralized.
  - Additionally, water lilies have been observed to grow in areas of this system with water depths exceeding three feet – a depth not conducive to WR plant growth. In a system with non-controlled water depth, water lilies may be a high proportion of the aquatic plant assemblage in the absence of WR. This could also be due to a lack of viable WR seed in the sediment; a potential result of WR germination in excessive water depths without subsequent reproductive success.
- Based on available data, and consideration of biological, physical, and other environmental influences beyond control specific to microbial H2S synthesis, application and enforcement of a sediment porewater sulfide WR protective level is unlikely to be beneficial to WR distribution in MN.

2. INFLUENCES ON WILD RICE GROWTH, HEALTH, AND ABUNDANCE

Increased focus on specific chemical characteristics of surface waters and associated sediment porewaters of wild rice (WR) areas may currently be non-warranted. Initially, system-wide physical and biological characteristics – specifically, water depth and competing vegetation – of waters containing WR should be the focus, if maintenance or management of that resource for WR production is the overall objective. Multiple examples of each of these influences can be observed occurring independently or, as is sometimes the case, concurrently

Based on historical, and current data and observations during laboratory and field experiments, as well as direct field-scale application via WR restoration activities, controlling competing vegetation and maintaining an appropriate water depth for WR should be the first two objectives for maintaining waters for increased WR growth, health, and abundance.

Initially, system-wide physical and biological characteristics of waters containing WR should be the focus, if maintenance or management of that resource for WR production is the overall objective. Specifically, water depth and competing vegetation.

According to published literature sources water depths of 0.5 – 3.0 feet are more conducive to WR growth and propagation (MN DNR 2008; Vogt 2012), and that water depth is the major factor controlling WR abundance and production (Aiken 1989, Oelke et al. 1997, MN DNR 2008; Vogt 2012).

Water depth directly influences WR phenological development and its ability to compete against other aquatic vegetation better able to cope with increased or increasing water depth.

Influences on WR from water depth increases depend on its phenology at the time of increase. If the increase is sudden during the submerged or floating leaf stage, the less developed roots may not be able to anchor the plant, which may then be uprooted (Thomas and Stewart 1969).

If water depth increase is more gradual and the plant is still in the submerged stage, it will take longer to reach the surface with corresponding losses in yields due mostly to decreased tillering, or complete loss of reproductive success due to mortality.

If the plant has achieved floating leaf stage and is then submerged, the plant is placed under stress since gas exchange with the atmosphere has been interrupted – NOTE: at this stage, the cuticle may have already formed further exacerbating WR plant stress due to decreased gas exchange ability while submerged. Some varieties survive by reducing growth and initiating metabolic processes that enable the plant to tolerate temporarily increased water depth.

… higher nutrient levels ensured more robust plant growth that enabled the plants to survive the water level increases. It may also be possible that the WR variety used had a genetic tolerance to depth increases such as shown by Counts and Lee (1988).

If water depth decreases to an extent that the water in the rice areas freezes to or past the sediment-water interface, the seed may desiccate (essentially the same as 'freezer burn') and lose its ability to germinate. In natural stands of WR, this is commonly known as the 'ring effect' whereby no WR grows along the shallower edges of the water body, but is present in some deeper sections (Aiken et al. 1989).

3. WILD RICE IN MN PRAIRIE POTHOLES

Primary factors limiting the restoration of WR in areas previously dominated by WR have been related to water depth and managing competing aquatic vegetation (see amended attachments – 'MN Conservation Volunteer – Wild Rice Renaissance,' and MPR News re: Fond du Lac Band WR restoration activities).

Moyle suggested that WR was primarily found in waters with a total alkalinity less than 40 mg l-1, pH between 6.8 – 7.0, and a sulfate concentration of less than 10 mg l-1.

The hydroponic solution recommended by Malvich and Percich (1993) uses a sulfate concentration of 48 mg l-1. Using this culture solution, Lee and Hughes (2000) found that early WR development was affected at sulfate concentrations in the range 1200 – 1500 mg l-1. Vicario and Halstead (1968) conducted experiments with rice in culture solutions with sulfate that ranged from 0 to 8800 mg l-1. They observed decreases in weight and height when sulfate in the culture solutions went above 220 mg l-1. More recent laboratory studies exposing WR seeds to various concentrations of sulfate and chloride salts under hydroponic conditions concluded that adverse influences from sulfate in particular occurred at concentrations over 1500 mg l-1 (Fort et al. 2014).

Overall, adverse influences on WR growth and development associated with sulfate and / or chloride are more likely due to a general increase in TDS, which tends to disrupt osmotic balance and ion transfer to / from / within the plant.

Lee (1979) in a survey of WR lakes in Minnesota and Ontario found the majority of lakes supporting WR had soft water with average alkalinities of 40 mg l-1 and pH levels of ~ 6.9.

Pip (1984) examined the distribution of 59 species of aquatic macrophytes, including WR, outside and inside the Precambrian shield of central Canada. She found the more important water chemistry parameters associated with their distribution to be pH, TDS, and total alkalinity.

Chloride, phosphorus, and sulfate concentrations were reported as '…of minor importance in both areas.' Wild rice is generally associated with more oligotrophic waters.

Pilsbury and McGuire (2009) attributed losses of WR in Minnesota and Wisconsin to residential and agricultural developments that increased nutrient levels, which can result in increased competition from other aquatic plants including algae. Ammonia and pH changes were specifically implicated.

Reduction in the range of WR has also been attributed to human disturbance including water contamination, recreational activities (boat turbulence), and importantly water level manipulation (Meeker 1996; Bennet et al. 2000).

Finally, although WR distribution may be influenced by water chemistry or at least correlated to water chemistry, WR also affects the water chemistry in which it lives. Lee and McNaughton (2004) showed that water surrounding WR stands contained lower sulfur (S), and higher conductivity, calcium, and iron concentrations than open water areas.

It is notable that there is a range of values for multiple parameters of one to three orders of magnitude suggesting that WR has a wide tolerance range of these characteristics.

All metals were therefore below levels where any adverse influence on WR should occur.

As typically isolated water bodies surrounded by agricultural activities, potholes may not be considered optimal, or even suitable, WR habitat for multiple reasons – the two primary reasons, as the initially more important reasons, are lack of water depth control and aquatic plant management. Influences from surrounding land use patterns may also contribute to the general non-suitability of potholes as WR habitat (nutrient inputs, pesticide / herbicide exposures, localized groundwater use); however, in the absence of data supporting these claims, discussion will be limited to the primary physical (water depth) and biological (competing aquatic vegetation) influences.

In general, in the absence of water depth control and maintenance of a preferable WR water depth, and the almost ephemeral nature of prairie potholes re: presence / absence of standing water, prairie potholes are unlikely to be acceptable habitat for WR production, regardless of chemical characteristics of overlying water, sediment, and sediment porewater.

Adverse influences from aquatic vegetation competing with WR for scarce resources can be exacerbated in the presence of non-controlled water depth.

4. WATER LILIES AS AN INDICATOR OF ACCEPTABLE WILD RICE HABITAT

Although water lilies can occur in the same general area as WR, and in some cases, co-occur, competing vegetation in general adversely influences the abundance of WR.

Additionally, water lilies have been observed to grow in areas of this system with water depths exceeding three feet – a depth not conducive to WR plant growth. In a system with noncontrolled water depth, water lilies may be a high proportion of the aquatic plant assemblage in the absence of WR.

In this particular area, WR and water lilies do occur in the same general area; however, a distinction between higher density populations of each plant appears evident. Due to this observation and the scenarios detailed above, simply stating that the presence of water lilies is an indicator of acceptable WR habitat is overgeneralized.

5. MIGHT THE 120 μg/ L SULFIDE PROTECTIVE LEVEL IMPROVE WR DISTRIBUTION IN MN?

Although as a general rule sulfide as hydrogen sulfide (H2S) can be problematic to organisms, there is a tolerance range associated with what may be the exposure concentration at which adverse responses are observed – WR in this case is no exception. Based on current MPCA field data and observations, WR can grow to a density of > 100 stems per square meter in the presence of hydrogen sulfide concentrations exceeding 120 μg / L.

Based on available data, and consideration of biological, physical, and other environmental influences beyond control specific to microbial H2S synthesis, application and enforcement of a sediment porewater sulfide WR protective level is unlikely to be beneficial to WR distribution in MN.

Since water depth is a primary controlling factor for WR distribution and abundance, and WR tends to prefer shallower water (0.5-3.0 feet deep), the likelihood of oxygenating the entire water column in areas of preferential WR habitat specifically during disturbance events would likely be high. Therefore, one controlling factor for hydrogen sulfide synthesis in nearer-surface sediments is likely water column oxygenation, both duration and frequency; in addition, sufficiently intense disturbance events could disrupt nearer-surface sediments, resulting in oxygenation of the disturbed sediment area and decreasing H2S synthesis potential.

ROL from WR plants could influence the overall composition of the microbial assemblage, further decreasing the potential for microbially mediated H2S synthesis during periods of growth for WR plants.

6. POTENTIAL INFLUENCES FROM IRON PLAQUE FORMATION ON WILD RICE ROOTS

Reduced iron precipitates have been observed to occur during the plant's life stage in which reproduction is the more dominant activity; during this time the seed is maturing, while the remaining portions of the plant are beginning to senesce. Precipitation of reduced iron species could be expected, since plant senescence during seed maturation involves decreased energy allocation to maintaining the shoot, stems, and leaves, and the likely decreased rate of ROL into the rhizosphere.

Although a lower nitrogen content of WR seeds may suggest a less 'healthy' seed, additional generational research is required to investigate influences on germination of viable WR seeds from plants exposed to increased aqueous sulfate, with generally decreased seed nitrogen. Since this was an observed association under more controlled laboratory conditions, field verification of these observations would be required to allow a more applied perspective to these data.

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[i] Pastor, 2014
[ii] Fort, et al, 2014

[iii] The “Ramboll equation”, detailed in Appendix 9 of the Technical Support Document
[iv] Reference page of the Pastor report
[v] KeeTac NPDEs permit, need reference
[vi] Reference needed
[vii] Independent research conducted by Barr Engineering, November 2016
[viii] Reference Pastor et al, 2013
[ix] Since UMD (and occasionally FEL) researchers chose to report sulfide values in uM (micromoles) instead of more conventional mg/l or µg/L values, values have been converted for clarity and consistency.

Comments on MPCA's Proposed Permanent Rules Relating to Wild Rice Sulfate Standard and Wild Rice Waters

In the Matter of Amendment of the sulfate water quality standard applicable to wild rice and identification of wild rice waters. Minn. R. chapters 7050 and 7053
(MN Revisor No. RD 4324A)
Office of Administrative Hearings Docket
No. OAH 80-9003-34519

Submitted On Behalf of Iron Mining Association of Minnesota by:
Michael J. Hansel
Principle Emeritus

November 21, 2017

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Comments on MPCA's Proposed Permanent Rules Relating to Wild Rice Sulfate Standard and Wild Rice Waters

November 21, 2017

Contents

1.0 Introduction and Overview

My name is Michael J. Hansel. I am a Principal Emeritus at Barr Engineering Co. I hold both a BS and MS in Chemical Engineering, and am a registered Professional Engineer in the state of Minnesota. I have over 40 years' experience in environmental engineering, working for the MPCA, the petroleum, power and mining industries as well as a consultant.

I have participated in Water Quality rulemakings since 1973, and have worked on wild rice issues since 2009. I participated (as an observer) in the MPCA's Advisory Committee. I was the chief drafter of the Minnesota Chamber of Commerce comments to the Advisory Committee and the MPCA throughout that process. I was a coauthor on Fort et al 2014[1] and Fort et al 2017[2] publications.

The proposed beneficial use of "wild rice waters[3]" protected "use of the grain of wild rice as a food source for wildlife and humans"[4][5] is uniquely Minnesotan. There is no federal beneficial use protecting wild rice, nor are there any other states which protect this particularly beneficial use.[6]

As such, MPCA cannot rely solely upon US Environmental Protection Agency (US EPA) rules or guidance. Instead, it must rely on Minnesota Law and state-of-the-art toxicology to determine what is needed to protect this beneficial use.

Minnesota law specifically directs the MPCA to review and revise the sulfate standard for wild rice in 2011, providing in part:

> "(a) Upon completion of the research referenced in paragraph (d), the commissioner of the Pollution Control Agency shall initiate a process to amend Minnesota Rules, chapter 7050. The amended rule shall:
>
> > (1) Address water quality standards for waters containing natural beds of wild rice, as well as for irrigation waters used for production of wild rice;
> >
> > (2) Designate each body of water, or specific portion thereof, to which wild rice water quality standards apply; and
> >
> > (3) Designate the specific times of year during which the standard applies.

[1] Reference (1)
[2] Reference (10)
[3] Proposed Minn. R. 7050.0130, Subp.6.b. 2017, MPCA, MN Revisor No. RD4324A Line 1.23 – 1.24
[4] Proposed Minn. R. 7050.0224, Subp. 5. A. MN Revisor No. RD4324A Line 7.18-7.19
[5] See also MPCA Statement of Need and Reasonableness (SONAR), 2017 at Section 6. C.1. at page 33-34
[6] Some Native American Tribes in Minnesota have wild rice rules which are, for the most part, consistent with the current rule.

> Nothing in this paragraph shall prevent the Pollution Control Agency from applying the narrative standard for all class 2 waters established in Minnesota Rules, part 7050.0150, subpart 3."[7]

Using monies provided by the Legislature, MPCA conducted the following experiments to determine the toxicity of sulfate to wild rice plants:

- Hydroponic sulfate toxicity experiments
- Hydroponic sulfide toxicity experiments
- Outdoor container experiments
- Field Surveys of wild rice habitats [8]

In addition, the Minnesota Chamber of Commerce (Chamber) commissioned Fort Environmental Labs to conduct hydroponic sulfate and sulfide toxicity studies, to confirm and/or correct the work done by MPCA and its contractors. Finally, MPCA relied upon published literature in its deliberations.

MPCA relied upon these "multiple lines of evidence" to determine a "protective" concentration of sulfide in the porewater of wild rice beds. The MPCA, assuming that sulfate in the water column is the source of sulfide found in sediment porewater, then uses statistical methods to derive, via back-calculation, a "protective" concentration of sulfate in the overlying water column.

> *"Ultimately, multiple lines of evidence, derived from field studies, outdoor container studies, and laboratory hydroponic studies, support the MPCA's decision that the protective level of sulfide for wild rice is 120 µg/L."*[9]

MPCA used a "weight-of-evidence" approach to "weight" or favor certain lines of evidence over other lines of evidence.

> *"EPA has consistently recommended "a 'weight-of-evidence' approach that considers all relevant information and its quality, consistent with the level of effort and complexity of detail appropriate in establishing and refining water quality standards." Information can be found in EPA's document entitled Weight of Evidence in Ecological Assessment."*[10][11]
>
> And
>
> See also "Figure 3. Estimates of protective sulfide concentrations for biological endpoints from hydroponic studies, outdoor container studies, and field data, based on EC10 estimates, change-

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[7] Laws of Minnesota, 2011 First Special Session, ch.2, article 4, section 32. See also the MPCA's Statement of Need and Reasonableness, Section 2.F, page 21 and following.
[8] Chapter 1.A of reference (2). page 4
[9] Section 6.E.2 of reference (3), page 67
[10] Id.
[11] Reference (11)

> point analysis, and visual examination of trends. (TSD)" and especially the footnote to that figure: "*Estimates marked with an asterisk (*) received less weight in the weighing of multiple lines of evidence due to limitations of the experiment or analysis. See TSD (Exhibit 1) for further discussion.*"[12]
>
> And
>
> See also "Table 1-8. Estimates of protective sulfide concentrations for wild rice from hydroponic studies, outdoor container studies, and field data, based on change-point analysis, EC10 estimates, and visual identification of a decrease in a graph of the proportion of field sites with wild rice present." and especially the footnote to that table: "*Estimates identified in the text as deserving less weight in the weighing of multiple lines of evidence.*"[13]

MPCA proposes to set a "protective" sulfate concentration in the overlying water column of wild rice waters, calculated from the "protective" sulfide concentration in pore water, as ameliorated by concentrations of iron in the sediment. The proposed water quality standard is:

> *"A. The standards in items B and C apply to wild rice waters identified in part 7.18 7050.0471 to protect the use of the grain of wild rice as a food source for wildlife and humans. The numeric sulfate standard for wild rice is designed to maintain sulfide concentrations in pore water at 120 micrograms per liter or less. The commissioner must maintain all numeric sulfate standards for wild rice waters on a public Web site."*[14]
>
> And
>
> "(1) the calculated sulfate standard, expressed as milligrams of sulfate ion 7.26 per liter (mg SO_4^{2-}/L), is determined by the following equation:
>
> Calculated sulfate standard = 0.0000121 x iron$^{1.923}$/organic carbon$^{1.197}$"[15]

1.1 Deletion of the current standard is needed and reasonable

MPCA proposes to delete the current standard of 10 mg/L[16]; this proposal is needed and reasonable and fully supported by the multiple lines of evidence.

1.2 The proposed new water quality standard is unneeded and unreasonable

The proposed new water quality standard is **<u>unneeded</u>** and **<u>unreasonable</u>** because:

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[12] Reference (2)
[13] Chapter 1.C. of reference (2) page 33
[14] Reference (15) , per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp. 5. B.1.
[15] Id., Subp. 5. B.1.
[16] Id., Subp. 2

- MPCA, though alerted by their own peer review panel, misconceptualized the hydrogeological conditions under which sulfate is delivered to sediment beds. This flawed conceptual model led to the following issues which pervade their analysis:
  - Unreasonably assuming that chemical diffusion of sulfate from an overlying water column to the sediment porewater is a process favored in these environments; and
  - Unreasonably excluding important controlling variables, such as the concentrations of iron and sulfate in groundwater, from field survey data collection.
- MPCA's model and key hypothesis are incorrect and are not supported out by the multiple lines of evidence;
- In considering the evidence, MPCA improperly weighted the multiple lines of evidence by:
  - Unreasonably excluding or discounting peer-reviewed published science that represents the state of the art in determining toxicity of chemicals to organisms;
  - Unreasonably relying too heavily upon non-peer-reviewed, unpublished science and analyses ;
  - Unreasonably failing to take into account other wild rice stressors, and ascribed all deleterious effects on wild rice to sulfide alone.

The MPCA never states (or proves) that the proposed "protective" porewater sulfide and water column sulfate are needed. MPCA's Statement of Need and Reasonableness (SONAR) lists only the following "needs" for the proposed rules:

> *"2. Statement of General Need*
>
> > *A. Need to protect the wild rice resource*
> >
> > *B. Need to revise the standard to reflect current scientific understanding of sulfate/sulfide*
> >
> > *C. Need to clarify the wild rice beneficial use and where it applies*
> >
> > *D. Need to clarify the application of the sulfate standard*
> >
> > *E. Need for a process to address wild rice waters identified in the future*
> >
> > *F. Need to address legislative mandates to undertake rulemaking*

G. Need to make supporting changes to Minnesota rules to facilitate development and implementation of effluent limits"[17]

Indeed, MPCA devotes only 2 paragraphs as to the need to revise the numeric standard, a total of 234 words, with absolutely **zero** discussion as to the need for a "protective" porewater sulfide and "protective" water column sulfate standard. While MPCA devotes much of the SONAR to discussion of the alleged reasonableness of the proposed standard, it gives short shrift as to the need for such a standard, and especially the need for the particular "protective" level of porewater sulfide and water column sulfate it proposes.

Each of the MPCA's hypothetical model and the multiple lines of evidence used to support that model are reviewed in these comments, clearly demonstrating that:

- MPCA's conceptual model does not correspond to natural conditions on wild rice waters;
- MPCA's hypothesis is not supported by the evidence; and
- MPCA unreasonably weighted the multiple lines of evidence; discounting sound science and unreasonably relying on questionable science and analyses.

Because of the MPCA's flawed analysis, discounting and reliance, the proposed "protective" level of sulfide and "protective" level of sulfate is unreasonable. Based on the MPCA's and other research, there is no need to regulate sulfate or sulfide to the levels proposed, because wild rice is not affected by sulfate or sulfide at those levels, only at much higher levels. And, even if a need can be shown, the proposed "protective" porewater sulfide and water column sulfate levels are unreasonable.

1.3 US EPA Guidance requires the use of controlled testing to determine toxicity

MPCA's initial research followed the state-of-the-art toxicity testing performed on aquatic organisms to determine whether individual substances, such as sulfate, are toxic to those organisms. US EPA has multiple publications, and relies upon other publications, to develop water quality criterion and to guide states in their development of such criterion.[18] These include:

- Organisms and Their Uses [19]

[17] Section 2 of reference (3), pages 19-22.

[18] US EPA distinguishes between water quality "standards" and water quality "criterion" as follows: "Water quality standards are regulations that include designated uses and water quality criteria to protect those uses. The criteria adopted and incorporated into the standards are the allowable concentrations of pollutants in State, Territory and authorized Tribal waters. These standards, which include water quality criteria, are adopted by the State, Territory or authorized Tribe and reviewed and approved or disapproved by EPA." See "Relationship between Water Quality Criteria and Water Quality Standards" US EPA at https://www.epa.gov/standards-water-body-health/relationship-between-water-quality-criteria-and-water-quality-standards . Thus, the numerical "protective" porewater sulfide and water column sulfate "standards" as proposed by the MPCA are actually criteria under US EPA nomenclature.

[19] Reference (4)

- Water Quality Standards Handbook - Chapter 3: Water Quality Criteria[20]
- Standard Guide for Conducting Acute Toxicity Tests on Test Materials with Fishes, Macroinvertebrates, and Amphibians[21]
- Short-term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Waters to Freshwater Organisms[22]
- Ecological Effects Test Guidelines[23]
- Selection of Water Quality Criteria in State Water Quality Standards [24]
- Technical Support Document for Water Quality-Based Toxics Control [25]
- Guidelines for Deriving Numerical National Water Quality Criteria for the Protection Of Aquatic Sulfate is not toxic to wild rice

Interestingly, MPCA only cites one of these publications: "Technical Support Document for Water Quality Based Toxics Control". It is clear that MPCA did not follow US EPA guidance on the development of water quality criteria, including the only one cited by them. Instead, MPCA seems to have embarked on a "voyage of discovery" to find some way to tie sulfate in the water column to alleged impacts to wild rice from sulfide in porewater, e.g. in the rooting zone. For example, even from the earliest parts of the process, the MPCA had unreasonably, and against a general and basic understanding of hydrogeology, implicated sulfate in the water column as the source of sulfide in the rooting zone: the 2014 Summary Report of the Meeting Peer Review MPCA's *Draft Analysis of the Wild Rice Sulfate Standard Study* contains this response from the MPCA to the technical reviewers: "MPCA was operating on the hypothesis that sulfate was diffusing down from the surface water into the sediment". While MPCA has determined that there may be a correlation between porewater sulfide concentration and wild rice growth, MPCA has not demonstrated how sulfide impacts wild rice, or how sulfate in the water column is the exclusive source of sulfate which gives rise to increased sulfide in the porewater.

US EPA's guidance and practice is to use hydroponic testing to determine the level at which specific chemicals impact biological organisms in water.

> "If it were feasible, a freshwater (or saltwater) numerical aquatic life national criterion* for a material should be determined by conducting field tests on a wide variety of unpolluted bodies of fresh (or salt) water. It would be necessary to add various amounts of the material to each body of water in order to determine the highest concentration that would not cause any unacceptable

[20] Reference (5)
[21] Reference (12)
[22] Reference (6)
[23] Reference (7)
[24] Reference (8)
[25] Reference (9)

long-term or short-term effect on the aquatic organisms or their uses. The lowest of these highest concentrations would become the freshwater (or saltwater) national aquatic life water quality criterion for that material, unless one or more of the lowest concentrations were judged to be outliers. Because it is **not** feasible to determine national criteria by conducting such field tests, these Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses (hereafter referred to as the National Guidelines) describe an objective, internally consistent, appropriate, and feasible way of deriving national criteria, which are intended to provide the same level of protection as the infeasible field testing approach described above.[26]

And

> "In each of two or more treatments, test organisms of one species are maintained for 2 to 8 days in one or more test chambers. In each of the one or more control treatments, the organisms are maintained in dilution water to which no test material has been added in order to provide (1) a measure of the acceptability of the test by giving an indication of the quality of the test organisms and the suitability of the dilution water, test conditions, handling procedures, and so forth, and (2) the basis for interpreting data obtained from the other treatments. In each of the one or more other treatments, the organisms are maintained in dilution water to which a selected concentration of test material has been added. Data concerning effects on the organisms in each test chamber are usually obtained periodically during the test and analyzed to determine LC50s, EC50s, or IC50s for various lengths of exposure."[27]

In fact, most of the water quality criteria were developed based upon some sort of hydroponic testing.[28] The reason for this is simple – it allows investigators to determine most precisely the level at which a specific chemical is toxic to aquatic life. US EPA notes in its guidance:

> "In addition, aquatic organisms in field situations might be stressed by diseases, parasites, predators, other pollutants, contaminated or insufficient food, and fluctuating and extreme conditions of flow, water quality, and temperature."[29]

Indeed, the literature on restoration of wild rice notes many of the stressors (e.g. fluctuating water conditions, predators, parasites) are important to the proper growth of wild rice.[30] MPCA also noted that several of these factors are statistically significant in their own field studies (e.g. fluctuating water levels, other pollutants).[31] About which, more anon.

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[26] Reference (4)
[27] Reference (12)
[28] Review of US EPA water quality criteria, including "Quality Criteria for Water, 1986and National Recommended Water Quality Criteria (reference (45).
[29] Reference (4)
[30] Reference (40), (41), Chapter 12 (Chapter 12: Wild Rice Community Restoration) of Reference (42), Reference (43)
[31] See Table 1-5 of reference (2). The 12 field variables that are significantly correlated with the presence/absence of wild rice, as determined through binary logistic regression,

2.0 Sulfate is not toxic to wild rice (at concentrations observed in Minnesota Wild Rice waters)

Two state-of-the-art scientific studies clearly demonstrate that sulfate is not toxic at concentrations observed in Minnesota wild rice waters. These studies were conducted in a laboratory where physical conditions were tightly controlled (e.g. temperature, light levels, periods of darkness). Chemical parameters of all other compounds were also strictly controlled, so that only sulfate concentrations varied. Biological parameters were also tightly controlled, with no competition from other competitive or invasive species and no disease parasites. Negative controls – where the wild rice is exposed to zero (or near zero) sulfate concentrations was grown under the same conditions as the exposed wild rice. One of the two, Fort et al[32], also used a positive control – where wild rice was exposed to a known toxicant, to be sure that the wild rice was not resistant to chemical toxicants. The Fort et al study also followed Good Laboratory Practices[33], an internationally recognized standard "to ensure the generation of high quality and reliable test data".

Dr. Pastor et al conducted a state-of-the-art controlled toxicity test, and concludes:

> *"Sulfate exposure concentrations of 0, 10, 50, 100, 400, and 1600 mg SO4/L did not affect germination success, mesocotyl lengths, or the masses of the stem plus leaf (if any) and roots (P > 0.10 for each test)."*[34]

Because Dr. Pastor et al struggled early on to grow wild rice in the laboratory, the Chamber commissioned Fort Environmental Labs to conduct similar hydroponic toxicity tests. Fort et al concluded:

> *"In summary, sulfate concentrations below 5000 mg/L did not adversely affect early–life stage wild rice during a 21-d [ay] period, and effects at 5000 mg/L sulfate were attributable to conductivity-related stress rather than sulfate toxicity in 2 of 4 end points."*[35]

There is excellent agreement between Dr. Pastor et al and Fort Labs et al that sulfate is not toxic to wild rice at concentrations seen in Minnesota waters. Dr. Myrbo found the highest concentration of sulfate in wild rice waters to be well under either the 1,600 mg/L sulfate found by Dr. Pastor and the 5,000 mg/L found by Fort Labs et al. The primary differences between the two studies is that Fort Labs et al tested higher concentrations than did Pastor et al, and also tested sodium chloride to determine that the toxic effects of sulfate were not due to sulfate per se, but due to salt related stress (conductivity related stress).

The toxic sulfate levels determined by both Pastor et al and Fort et al, using standard toxicological testing, are more than 1,000 times the current standard of 10 mg/L. It is also interesting that the toxic sulfate levels determined by both Pastor et al and Fort et al, using standard toxicological testing, are more than

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[32] Reference (1)
[33] See OECD webpage at http://www.oecd.org/chemicalsafety/testing/good-laboratory-practiceglp.htm
[34] Reference (13)
[35] Reference (1)

1,000 times the median sulfate concentration in streams (17 mg/L) and lakes (3 mg/L).[36] Those same levels are more than double the highest level measured by Myrbo et al. – 838 mg/L at Second Creek.[37]

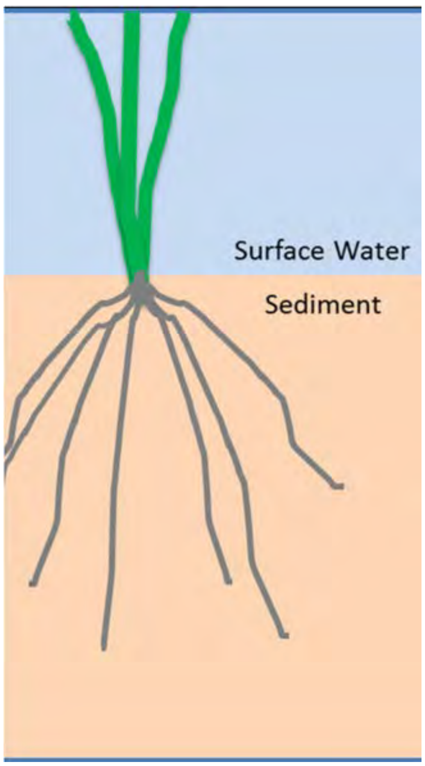
Based on these controlled sulfate hydroponic experiments, there is absolutely no scientific support for the current standard of 10 mg/L sulfate in the water column. Nor is there any scientific support for the notion that sulfate is toxic to wild rice at concentrations observed in Minnesota wild rice waters. Therefore, the current standard of 10 mg/L sulfate[38] (proposed Minn. R. 7050.0224, Subp.2) should be struck as MPCA proposes; there is ample evidence of the need for and reasonableness of its elimination.

[36] Chapter 1.A. of reference (2), page 7.
[37] Raw data from reference (14)
[38] Reference (15) per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp. 2

3.0 Sulfide is not toxic to wild rice (at concentrations observed in Minnesota Wild Rice Waters)

)

It may be instructive to be reminded of what a wild rice plant looks like, and how it grows. At the end of a growing season, unharvested wild rice seeds fall to the sediment in the wild rice water, and spend the winter in or on the sediment. Because wild rice seeds are so light, they do not penetrate very far into the sediment – a matter of a few centimeters, if at all. The seeds overwinter in or on the sediment, and when the overlying water warms in the spring, the seeds sprout. The seed sprouts a mesocotyl (the first leaf and bit of stem) and roots. The shoot extends up through the water and spreads leaves out on the surface of the water – the "floating leaf" stage of growth. Eventually the shoot extends above the water, where additional leaves and flowers form, and seeds are pollinated and set. See the figure below. [39]



As can be seen, the only parts of the wild rice plants that reside in or on the sediment are:

- The seed
- The roots

[39] Table 1-7 of reference (2). page 42

- The mesocotyl

The only processes which operate in or on the sediment are:

- Sprouting
- Mesocotyl growth
- Root growth

All other processes occur above the sediment, either in the water or in the air above the water. Those processes above the sediment are exposed to oxygen – either oxygen in the air or oxygen dissolved in the water. Because of the presence of oxygen, sulfide does not exist in any appreciable amount – it is almost immediately oxidized to sulfate. Thus the only portions of the wild rice plant which could be exposed to sulfide are the seeds, the roots and the early mesocotyl growth.

MPCA's contractors conducted similar state-of-the-art controlled tests for the toxicity of sulfide. When Dr. Pastor began his hydroponic sulfide studies, he attempted to imitate the natural process, sprouting and growing seeds in a jar containing anaerobic solutions with varying concentrations of sulfide, and allowing the shoots to grow through a sealed lid so that the plant (above the mesocotyl) was in air.[40] Unfortunately, Dr. Pastor was not able to grow wild rice in this manner, and so changed the experiment such that the entire plant, from sprouting seeds to 10 to 11 day's growth, was sealed inside a container, with the entire plant exposed to anaerobic conditions with varying concentrations of sulfide.

The Peer Review Panel had serious concerns about Dr. Pastor's hydroponic study, and recommended that "If these experiments can be repeated, the panel recommends the following approach:

- Use of **a split design**, in which there is a root compartment separated from the shoot. This allows **anaerobic conditions in the root zone to be maintained** and exposure of the root (but not shoots) to the experimental sulfide concentrations.
- Use of an **experimental period of 14 or 21 days**, which is standard in ecotoxicology for aquatic macrophytes. Response measurements should be collected at regular intervals.
- To the extent possible, **use of the same biological endpoints** in the laboratory study as used in the outdoor container and field studies. Decisions on biological endpoints for all the field and laboratory studies in turn will feed into the modeling approaches that can be used. This should be part of the conceptual framework and design for the overall Study and will allow better integration of the study components.

[40] Meeting of MPCA Advisory Committee, 2012. Duluth, MN

- **A larger sample size**. A power analysis should be done to determine the number of replicates and treatment levels needed.

- We anticipate that **a minimum of six exposure concentrations** should be used, with several treatment levels bracketing the current water quality standard.

- **Maintaining the exposure concentrations throughout the experimental period**. This will be easier if roots are separated from shoots."[41] (Emphasis added)

The Peer Review Panel was chosen by a contractor to the MPCA, and included international experts on wild rice and rice production.[42] At the time, MPCA indicated that it would rely upon the opinions of these experts in weighting the multiple lines of evidence.

However, the MPCA and Dr. Pastor chose not to repeat the experiment, or to implement the recommendations of the Peer Review Panel. The Chamber engaged Fort Environmental Labs to undertake a further hydroponic study on the toxic effects of sulfide. At that point, the MPCA had revised its hypothesis: that the "that sulfide concentration is a function of the level of sulfate in the overlying water, and the concentrations of carbon and iron in the sediment."[43] Accordingly, Fort Labs also varied the amount of iron and organic carbon along with sulfide in the experiment.

The results of the Fort Labs study found that at Day 10, with no additional iron, emergence of seedlings was most affected by sulfide, but the lowest observed effects concentration (LOEC) was 3.2 mg/L sulfide.[44]

> *"Increasing Fe concentrations reduced the toxic effects of sulfide to wild rice,"[45] with day 10 LOEC for emergence of seedlings rising to 7.8 mg/L sulfide.*

MPCA effectively dismisses the Fort Lab study:

> *"However, under natural conditions, 21-day old wild rice plants would not have access to the atmosphere because the stems would not yet have elongated sufficiently to reach the water surface. Therefore, it is unlikely that 3-week old plants would have access to sufficient oxygen to detoxify such high levels of sulfide. … the [Fort et al] is not given great weight among the multiple lines of evidence."[46]*

MPCA's essential rejection of the Fort et al sulfide hydroponic study is not reasonable. First, Fort Labs followed as nearly as possible the recommendations of the Peer Review Panel. Second, the Fort Labs study followed Good Laboratory practices and was certified as such. Third, the Fort Labs study followed

[41] Reference (16)
[42] Reference (16)
[43] Section1.B of reference (3). page 12
[44] Reference (10)
[45] Id.
[46] Section 6.E.2 of reference (3). page 71

US EPA guidance for conduct of toxicity testing for the purpose of developing water quality criterion and standards.

While the wild rice plants would not have access to the atmosphere in a natural setting, they would have access to both oxygenated water (e.g., the water above the sediment) and sunlight (allowing the plants to photosynthesize, producing oxygen). It is well documented that aquatic macrophytes can supply oxygen to the root system.[47] Indeed, Dr. Pastor found that in his sulfide hydroponic studies:

> *"Because the plants were photosynthesizing and producing oxygen, the sulfide concentration declined during these two–three day periods."*[48]

Because 10 and 21 day old seedlings in the wild **would** have had access to oxygen, or could have produced their own oxygen, it is unreasonable for the MPCA to effectively dismiss the Fort et al studies. The Fort et al studies remain scientifically valid, have been peer reviewed and published, and MPCA unreasonably rejected their findings.

Interestingly, despite the fundamental flaws in Dr. Pastor's sulfide hydroponic studies, he found similar results for those parts of the plant which are in contact with the sediment:

> *"Sulfide concentrations of 0, 96, 320, 960, and 2880 µg/L did* ***not*** *affect* ***germination success of seeds, mesocotyl masses, or mesocotyl lengths*** *(P > 0.10 for each test)."*[49] (Emphasis added)
>
> And
>
> *"****Root lengths were only weakly depressed with increasing sulfide concentration*** *(P < 0.10)."*[50] (Emphasis added)

Thus, based on the hydroponic tests conducted by Pastor et al and Fort Labs et al, sulfide is not toxic "in the root zone" or "in the sediment" to those parts of the wild rice plant that lives there, at concentrations of 2,800 µg/L to 3,200 µg/L – hundreds of times more than the "protective" level of sulfide proposed by the MPCA – 120 µg/L. These levels are more than 50 times the median concentration determined during the field surveys conducted by Myrbo as well. Setting aside the two outlier lakes (which had sulfide concentrations more than 10 times higher than any other water body surveyed), these levels are nearly double the sulfide concentration found in wild rice waters.

Based on these controlled sulfate hydroponic experiments, there is absolutely no scientific support for the proposed "protective" sulfide standard of 120 µg/L sulfide pore water[51]. Nor is there any scientific support for the notion that sulfide is toxic to wild rice at concentrations observed in Minnesota wild rice waters.

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[47] Reference (25)
[48] Reference (13)
[49] Id at 1.
[50] Id
[51] Reference (15), per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp. 5.A

Therefore, MPCA has not demonstrated the need for or reasonableness of the proposed "protective" sulfide standard of 120 µg/L sulfide in the porewater[52].

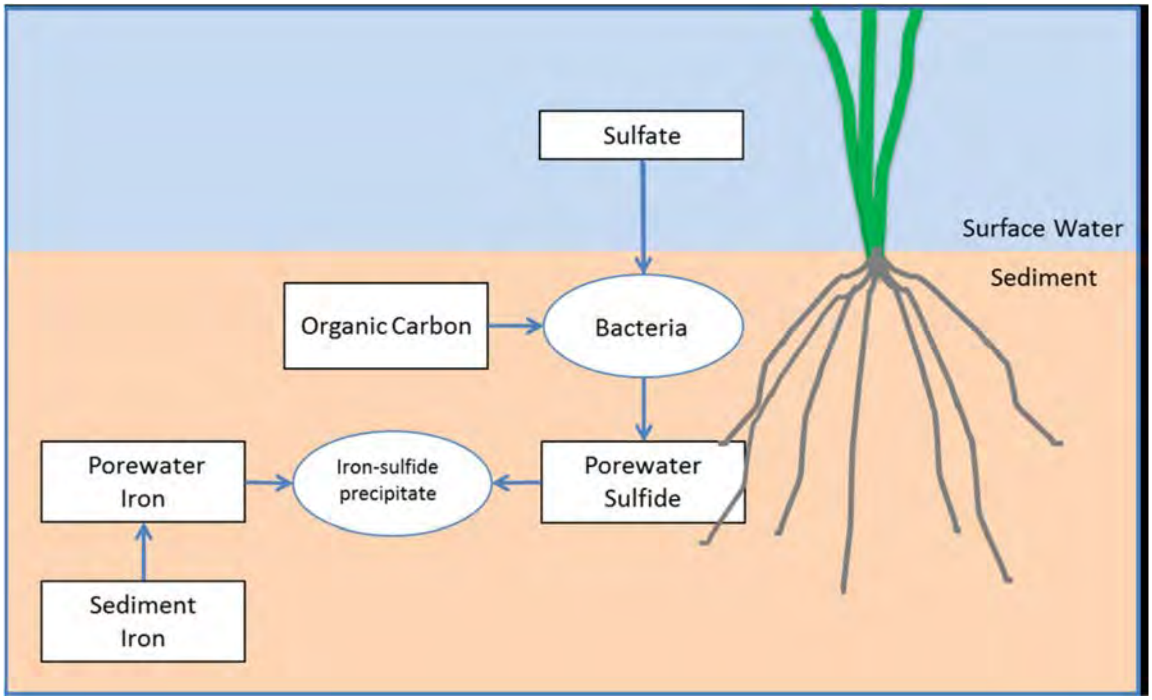
Based on these state-of-the-art controlled sulfide hydroponic experiments, the need for and reasonableness of the proposed "protective" sulfate standard:

Calculated sulfate standard = 0.0000121 x iron$^{1.923}$/organic carbon$^{1.197}$"[53], has not been demonstrated.

[52] Id.
[53] Reference (15), per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp. 5. B.1.

4.0 MPCA's Conceptual Model and Key Hypothesis do not correspond to natural conditions

MPCA has developed and relied upon a model of how wild rice interacts with the environment in wild rice waters. This model is summarized in Figure 1-7 of the Technical Support Document[54] (TSD), reproduced below:



Source: Figure 1-7 of reference (1)

Conceptual model of the primary variables affecting the relationship between surface water sulfate and porewater sulfide. .

This conceptual model underwent much scrutiny by the Peer Review Panel (PRP) which the MPCA employed during the development of this rule. On the issue of the utility of the field survey data, which the MPCA heavily relies on in developing the proposed standard. The PRP asked specifically for clarification about groundwater:

> *"Did MPCA consider how sulfate loadings from groundwater may influence sulfate and sulfide concentrations in surface waters and sediment porewaters?*

[54] Reference (2)

MPCA Response: *MPCA recognized that groundwater movements into or out of surface waters may influence surface water and sediment porewater concentrations of sulfate and sulfide, but did not have a reliable method of assessing groundwater movement, especially for sulfate and sulfide."*[55]

Setting aside the fact that reliable methods, including seepage meters, groundwater wells, and robust modeling methods have been developed and used by hydrologists for decades[56], the MPCA's analysis has yet to address sulfate in groundwater and its likely control of both the concentrations of sulfide in sediment porewater and sulfate in the surface water column.

This is the heart of the problem: in northern Minnesota, groundwater is constantly, and nearly everywhere, discharging to streams and lakes because groundwater water table elevations are higher than adjacent surface water levels, leading to hydraulic pressure that favors this discharge[57]. Coupled with the fact that this groundwater carries with it 1-100 mg/L sulfate in this region[58], *it* is likely that groundwater is the dominant control on porewater sulfate and sulfide concentrations, and, to a large degree, also likely controls sulfate concentrations in the surface water column.

A recent study by the Minnesota Department of Natural Resources (MDNR) explicitly states that while point discharges "are the dominant source of sulfate to sites downstream from them, it appears that the background sulfate. . .has the largest influence" on sediment porewater chemistry, and the conversion of sulfate to sulfide (Berndt et al., 2016). "This is because point sourced sulfate is transported generally under oxidized conditions and is not flushed through riparian sediments in a gaining stream watershed system."[59]

In stark contrast, MPCA's conceptual model relies on sulfate delivery **to the sediment bed from the overlying water column through chemical diffusion**; nowhere does MPCA demonstrate that this mechanism is reasonable. The MPCA also neglects the groundwater contributions of dissolved iron.

The MPCA model gives rise to the following oversights and interpretive errors in the MPCA's analysis:

- Because of the "a prior assumption" assumption and untested hypothesis about the source of sulfate in the sediment porewater, MPCA neglected to collect pertinent information on groundwater quality and groundwater advection rates during the field survey. Although the PRP specifically pointed out the oversight, MPCA continued to neglect to collect the reasonably needed data. Even though these data were not collected, they cannot be ruled out as dominant factors controlling the chemistry of the sediment porewater (e.g. nutrients, iron and other metals). Most hydrologists would recognize that groundwater is the dominant control[60].

[55] Reference (16), page 15.
[56] Reference (18)
[57] Reference (19)
[58] Reference (20)
[59] Reference (17), pages 74-79
[60] Linking soil- and stream-water chemistry based on a riparian flow-concentration integration model. Reference (21).

- Because those data were not collected, they were not included in statistical analysis such as the regression analyses or the structural equation modelling that resulted in the proposed equation. Therefore, the analysis does not include a likely controlling factor - a "lurking" third factor that controls both the dependent and independent variables in the study.

So, the MPCA's supposition that a tenuous correlation between water column sulfate and porewater sulfide indicates that the "equation works 80% of the time" is problematic. The tenuous correlation found by MPCA may simply reflect two factors that are controlled by the underlying (and unmeasured) influence of groundwater.

Under MPCA's conceptual model, and in the resulting proposed equation-based sulfate standard, **sulfate migrates via diffusion *only* from the overlying water column** where it is converted by microorganisms in the sediment to sulfide, using organic carbon from the sediment. **There are no other sources of sulfate** which can move into the sediment, and no other sources of organic carbon that can move into the sediment.

Similarly, under MPCA's model, **organic carbon *only* moves from the sediment to the porewater**. **There are no other sources of dissolved organic carbon**. And, under MPCA's model, **iron *only* moves from the sediment to the porewater** and reacts with sulfide to precipitate the sulfide and make it unavailable to interact with wild rice or other biota. **There are no other sources of iron** which can move into the porewater and interact with sulfide.

This model gives rise to MPCA's key hypothesis regarding the impact of sulfate on wild rice:

> *"MPCA staff had a hypothesis, stated in the study protocol informed by researchers, tribes and stakeholders, (Exhibit 7) that **sulfate exerts negative effects on wild rice** when it is converted to hydrogen sulfide, which is much more toxic than sulfate. In mucky low-oxygen environments, such as those favored by wild rice (which roots in the sediment of aquatic habitats), the respiration of sulfate reducing bacteria in the sediment converts **sulfate diffusing into the sediment from the overlying water into hydrogen sulfide in the sediment porewater**.*
>
> *"The sulfide concentration in the porewater, the water in the sediment between solid particles, is key because it is the porewater that is in contact with the roots of wild rice. The wild rice study and research supported the MPCA staff's hypothesis, showing that the pollutant that harms wild rice is sulfide in the sediment porewater."*[61] (Emphasis added)

Neither MPCA's conceptual model nor key hypothesis is a reasonable depiction of the natural conditions in wild rice waters. They were specifically called into question by the technical peer review panel, who explicitly identified that the field study "requires addressing the full hydrological system (supply by surface water and groundwater)". the conceptual model used by the MPCA is not borne out in the general

[61] Reference (3)

understanding of the hydrologic cycle, in decades of research on Minnesota lakes and rivers by USGS and other researchers, or by recent research published by the Minnesota DNR[62].

4.1 MPCA's Conceptual Model of wild rice waters as "bathtubs" does not reflect natural conditions

In natural wild rice beds (both in streams and lakes), groundwater flows into sediment porewater, generally from the area of high hydraulic head (the groundwater) to the area of low hydraulic head (the surface water body). [63] MPCA acknowledges that wild rice appears to be associated with areas of groundwater inflow:

> *"Wild rice is in a group of emergent plant species that had a mild statistical association with groundwater inflow areas of lakes"*[64][65]

In fact, the reference cited by the MPCA in its TSD goes further:

> *"Emergent and isoetid (Adams 1985) species* ***may be the most likely to be influenced by groundwater flow****. Both plant types were not well represented in this study. Emergent species are found in shallow water where groundwater flow is often the strongest (McBride and Pfannkuch 1975) and they are dependent on roots for nitrogen and phosphorus, whereas many submersed species can obtain nutrients from the water column if they are more abundant in the water than in the underlying sediment." (NB: wild rice is an emergent aquatic macrophytes)* (Emphasis added)
>
> And
>
> *"This study showed a group of emergent species including Pontederia cordata, Eleocharis palustris, Sagittaria graminea, Carex aquatilis, Typha latifolia, and* ***Zizania spp****. [e.g.* ***wild rice****] that was mildly associated with shallow water, groundwater inflow areas."*[66] (Emphasis and insert added)

Unfortunately, the MPCA treats their dataset as if wild rice waters are essentially "bathtubs" with no interaction between groundwater and surface water, and no interaction between groundwater and sediment and porewater. Thus, MPCA's model ignores the important role of groundwater in bringing nutrients and sulfate into the sediment and porewater. It is unlikely that sulfate from the surface water is the primary source for the formation of sulfide.

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[62] Reference (17)
[63] Reference (18).
[64] Table 1-6 of reference (2), page 26,:
[65] Reference (22)
[66] Reference (22)

In fact, this scenario almost never exists, because water bodies dominantly "gain" water from groundwater in this region. Groundwater is well known to interact with sediment porewater. There is strong evidence of groundwater interaction with the water column (surface water) and sediment and porewater.[67]

4.2 Literature demonstrates that groundwater interacts with sediment and wild rice

One of the references cited by Nichols and Shaw[68] describes the interaction between groundwater and wild rice waters:

> *"The mutual exchange of water between lakes and contiguous permeable ground-water bodies, which are thin relative to the diameter of the lakes, was modeled digitally.* ***A significant rate of seepage was found to extend only a relatively short distance from shore, thus forming a narrow band around the lake's perimeter.*** *This near-shore concentration of seepage is an effect only of the geometry of the ground-water flow system, which is governed by the geometry of the body of permeable material, the spatial distribution of permeability within it, and the form of the water table. Near-shore seepage occurs independently of the presence of fine-grained, low permeability sedimentary bottom materials in the central part of the lake. Digital modeling indicates that the velocity of seepage generally decreases at an exponential rate as a function of distance from shore.* ***Field measurements of seepage rates through the bottom of Lake Sallie, west-central Minnesota, confirm the model results by demonstrating that both the near-shore seepage band and the exponential decrease in seepage velocity actually exist****."*[69] (Emphasis added)

The "near-shore seepage band" is precisely where wild rice grows. A recent publication by Berndt et al. (2016) reaches similar conclusions.

> *" .* ***<u>stream segments along the flow path mostly gain water from the surrounding landscape</u>****. The hydraulic gradient is, therefore, well poised to produce and transport chemicals . . . to the river, but water [in the water column] is not well poised hydrologically to interact with riparian sediments."*[70] (Emphasis added)

Thus, MPCA's model is fundamentally flawed, because it unreasonably implicates the water column as the source of sulfate. It ignores the important role of groundwater in bringing nutrients and sulfate into the sediment and porewater.

MPCA appears to acknowledge that groundwater flow can be significant, when it authorizes an alternate standard (see proposed rule MN Rules 7050.0224, Subp. 5. B.2:

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[67] Reference (17)
[68] Reference (22)
[69] Reference (22)
[70] Reference (17)

"(2) The commissioner may establish an alternate sulfate standard for a wild rice water when the ambient sulfate concentration is above the calculated sulfate standard and data demonstrates that sulfide concentrations in pore water are 120 micrograms per liter or less. Data must be gathered using the procedures specified in Sampling and Analytical Methods for Wild Rice Waters, which is incorporated by reference in item E. The alternate sulfate standard established must be either the annual average sulfate concentration in the ambient water or a level of sulfate the commissioner has determined will maintain the sulfide concentrations in pore water at or below 120 micrograms per liter."[71]

The SONAR states that the commissioner may develop an alternate standard, and notes that groundwater influence is the reason for the need for and reasonableness of the provision. At page 14 of the SONAR:

"As an alternative to the equation-derived numeric standard, the proposed rule allows the commissioner to establish an alternate standard based on the actual amount of sulfide in the sediment porewater. The equation-based numeric standard is designed for the vast majority of water bodies, where changes in the porewater sulfide concentration is proportional to changes in sulfate in surface water. An alternate standard may be appropriate ***<u>when the sulfide in the sediment porewater is being controlled by sulfate in the groundwater</u>****, rather than surface water."* [72]*(Emphasis added)*

At page 33:

*"The proposal establishes a process for developing an alternate standard where evidence exists that porewater sulfide is at or below 120 µg /L without reference to surface water sulfate levels (***<u>as when groundwater is a heavy influence on sediment porewater</u>***).*[73] (Emphasis added)

At pages 89 to 91 of the SONAR, MPCA is clear why the alternate standard is needed and reasonable:

"A water body that consistently exhibits porewater sulfide less than 120 µg/L when the equation predicts sulfide greater than 120 µg/L is ***<u>most likely experiencing the upward movement of groundwater through the sediment</u>****."*[74] (Emphasis added)

And

"The ability to set an alternate standard responds to concerns about false positives (where surface water sulfate above the calculated standard does not elevate porewater sulfide) that ***<u>potentially could cause investment in sulfate control that is not needed to protect wild rice.</u>*** *The MPCA is aware of sites where the relationships established by the equation do not hold true; that is, where*

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[71] Proposed Permanent Rules Relating to Wild Rice Sulfate Standard and Wild Rice Waters MN State Revisor No. RD 4324A, lines 8.18 to 8.25
[72] Reference (3)
[73] Id
[74] Id

sulfate does not convert to expected levels of sulfide based on the equation. ***<u>This is usually due to circumstances specific to the water body, such as groundwater flow that counteracts the diffusion of surface water sulfate into the sediment</u>****."*[75] (Emphasis added)

And

"False positives may also be the result of the ***<u>failure of a waterbody to conform to the conceptual model</u>*** *upon which the equation is based".*[76] (Emphasis added)

We respectfully suggest that the failure is more likely of the conceptual model and hypothesis, not the water body.

The technical support document (TSD) attempts to provide the evidence that the MPCA's model is correct, reasonable and needed. However, it is essentially a tautology. MPCA argues that because certain waters don't fit the model (e.g. exhibit "false positives"), the model is correct and the waters that don't fit the model (because groundwater inflow to the sediment prevents the formation of sulfide at levels which have the potential to harm wild rice) are "outliers". Indeed, MPCA presents only one measurement to demonstrate that this occurs; a measurement of Second Creek (see Yourd, 2017)[77]. Those measurements showed that porewater sulfide was lower than the "protective" level of 120 µg/L, "porewater sulfide was less than 120 µg/L in each case despite relatively high sulfate concentrations (303 to 838 mg/L; sulfate was not measured for one of the samplings)."[78]

MPCA makes other admissions in the TSD regarding groundwater flow being an important consideration in the geochemistry of porewater – one that is not reflected in the MPCA's model. For example, on page 1, MPCA admits:

"Sulfate is a natural chemical ***<u>commonly found</u>*** ***<u>in</u>*** *surface and* ***<u>groundwater</u>****." (Emphasis added)*

In Table 1-1 (under outdoor container experiment column), MPCA admits that the container study has the following limitations:

"Eventual steady states with various sulfate loads may not mimic the environment, ***<u>since there is no loading of other key constituents, such as iron, from groundwater</u>*** *or the watershed."* (Emphasis added)

And under the Sediment incubation laboratory experiment column, MPCA admits the groundwater is a key missing component

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[75] Id.
[76] Id.
[77] Reference (36)
[78] Reference (2), page 69

"Provides preliminary assessment of sediment from two sites that may inform, ***<u>but is not fully transferrable to other sites; no groundwater movement</u>****; no wild rice plants grown."* (Emphasis added)

On page 23

"However, ***<u>one exception may be sites with upwelling groundwater; it has been reported that such sites may be favorable habitat for wild rice</u>*** *(Table 1-6).* ***<u>Consistent upward groundwater flow would break the usual relationship between sulfate in surface water and sulfide in porewater, because sulfate would be less likely to move downwards into the sediment when groundwater is moving upwards. Therefore, at some sites the sulfate concentration of the groundwater may be more important than the surface water in controlling the production of porewater sulfide</u>****, but statistical analysis shows that at most sites porewater sulfide is a function of surface water sulfate (Pollman et al., in press). … Even if this were not the case, the* ***<u>possibility that groundwater, rather than surface water, controls porewater sulfide in a specific wild rice bed does not negate the validity of the empirically observed, statistically significant</u>****, relationship between surface water sulfate, sediment iron, sediment TOC, and* ***<u>porewater sulfide as a general matter</u>*** *(Part D of this chapter, below; Pollman et al., in press)."* (Emphasis added)

In other words, groundwater "upwelling" through the sediment has been observed as a critical component in the growth of wild rice. Yet, despite the measurements of multiple lakes in Wisconsin and multiple streams and lakes in Minnesota, MPCA holds that the model is still "valid" because of the MPCA's and Dr. Pollman's statistical analysis.

In Table 1-6 on page 26, MPCA admits that it has made no measurements of groundwater flow in the field surveys, and that upward groundwater flow would invalidate the model:

*"****<u>No information was collected on groundwater movement at the field sites</u>****.* ***<u>Upward flow would break the usual relationship</u>*** *between surface water sulfate and sulfide, because sulfate would be less likely to move downwards into the sediment when groundwater is moving upwards." (Emphasis added)*

Not only does groundwater movement through the sediment prevent chemical diffusion of surface water (and associated sulfate) into the sediment, but groundwater also brings with it other chemicals which participate in the reaction to form or prevent the formation of sulfide. On page 53 of the TSD:

"For instance, an isolated bay of a wild rice water could plausibly have ***<u>low sediment iron concentrations because the local watershed is poor in iron or there is no emergent groundwater rich in iron</u>*** *(Maranger et al., 2006)."* (Emphasis added)

At page 67 of the TSD, MPCA admits that sulfate will not move from the water column into the sediment when groundwater is moving into the sediment:

*"False positives were consistently observed in four of the waterbodies. These four waterbodies consistently had porewater sulfide below 120 µg/L, despite predicted sulfide concentrations above that threshold (Table 2-1). Wild rice was growing in all four of the waterbodies. The most reasonable explanation for unexpectedly low porewater sulfide in these waterbodies is that **surface water sulfate was not penetrating downward into the sediment because of upwelling groundwater**."* (Emphasis added)

On page 69 of the TSD, the MPCA admits that the model is based upon assumption, not evidence, not measurements:

*"**The model is based on the assumption that** porewater sulfide is produced by bacteria in the sediment that are utilizing **sulfate transported from the surface water downwards into the sediment**. However, **there may be wild rice waters where groundwater actively moves upward through the sediment, in which case sulfate in surface water would not play a major role in the production of sulfide**. In such cases, ambient sulfate in surface water in comparison to the calculated sulfate standard can produce false positives, depending on the sediment concentrations of organic carbon and extractable iron. **Wild rice waters with upwelling groundwater might be most often encountered in gaining streams, which receive water from groundwater, and some lakes that receive groundwater**. The interaction of groundwater and surface waters is complicated, and is a function of multiple variables such as the texture and depth of soils, topography, and even seasonal growth of plants that transpire large amounts of groundwater, such as willows (Fetter, 2001).* (Emphasis added)

Most water bodies (both streams and lakes) in Minnesota (except southeast Minnesota) are gaining. In Table 2-1 of the TSD MPCA notes multiple reasons why the model is incorrect, yet treats these:

*"Waterbodies are clustered into three categories in an effort to understand why false positives were produced: 1) Four waterbodies for which **the likely explanation is that groundwater was upwelling through the sediment**, so that the sites were not accurately modeled by the proposed equation; 2) Four waterbodies for which the likely explanation is random error because sulfate level is only slightly greater than the calculated protective concentration; and 3) **Six waterbodies**, each of which were sampled at least three times, **that exhibited inconsistent behavior,** which might be resolved with more extensive sampling. (CPSC120 = Calculated Protective Sulfate Concentration associated with a protective sulfide concentration of 120 µg/L)".*

Note that there are 15 such lakes, of the 67 lakes which MPCA sampled which actually contained wild rice. Thus, 22% of the wild rice waters don't behave as the model suggests, which caused the MPCA to include an "alternate" standard, which is not found in any other Minnesota water quality standard or US EPA water quality criterion:

"The commissioner may establish an alternate sulfate standard for a wild rice water when the ambient sulfate concentration is above the calculated sulfate standard and data demonstrates that sulfide concentrations in pore water are 120 micrograms per liter or less. Data must be gathered

using the procedures specified in Sampling and Analytical Methods for Wild Rice Waters, which is incorporated by reference in item E. The alternate sulfate standard established must be either the annual average sulfate concentration in the ambient water or a level of sulfate the commissioner has determined will maintain the sulfide concentrations in pore water at or below 120 micrograms per liter."[79]

Pollman et al also note the fact that groundwater discharge is "important" for replenishment of iron and other substances:

> *"This is an extension of the fact that sediment Fe must be present for dissolved Fe(II) concentrations to develop in the porewater,* ***<u>unless an alternative source of dissolved Fe(II) such as via shallow groundwater discharge is important</u>****), ref: Appelo, C. A. J. and H. Postma (2010), Geochemistry, groundwater and pollution. Second edition. CRC Press, Boca Raton, FL. 649 pp."* [80] (Emphasis added)

Berndt et al found that this was exactly the case in the St. Louis River system in northeastern Minnesota.

> *"It was found that peaks in measured methylmercury (MeHg), total mercury (THg),* ***<u>dissolved organic carbon (DOC), and dissolved iron (Fe) concentrations correspond to periods in time when modeled recharge was dominated by active groundwater throughout the watershed.</u>***

> *"Taken together, the data and flow model imply that MeHg is released into groundwater that recharges the river through riparian sediments following periods of elevated summer rainfall. The measured sulfate concentrations at the upstream site reached minimum concentrations of approximately 1 mg/L just as MeHg reached its peak,* ***<u>suggesting that reduction of sulfate from non-point sources exerts an important influence</u>*** *on MeHg concentrations at this site. While mines are the dominant source of sulfate to sites downstream from them****<u>, it appears that the background sulfate which is present at only 1-6 mg/L, has the largest influence</u>*** *on MeHg concentrations. This is because* ***<u>point sourced sulfate is transported generally under oxidized conditions and is not flushed through riparian sediments in a gaining stream</u>*** *watershed system.* (Emphasis added)

> *"According to these models,* ***<u>groundwater that enters a river in its headwater regions attains much of its chemistry by reaction with riparian sediments, the last substrate with which it is in contact prior to becoming part of the surface water flowage</u>****. Thus, a comparison of measured chemistry to HSPF modeling results can help to determine the degree to which similar processes might help to account for the chemistry of water in mine-impacted portions of the St. Louis River."* (Emphasis added)

> *"CAG [concentration in active groundwater] values close to 1.0 throughout the region indicate that* ***<u>active groundwater was the overwhelmingly dominant source of water input during most</u>***

[79] Reference (15), per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp. 5. B.1.
[80] Reference (39)

periods from April through July. Overland surface runoff and interflow waters were common immediately following large rain events, but these were flushed quickly downstream by more persistent, longer lasting recharge from active groundwater flow*."* (Emphasis and parenthetical added)

"Calculated transit times for groundwater-derived components were generally 10 days or less at all sites from April through July." (E.g. the early growing season for wild rice)

"Active groundwater tracer concentrations calculated for each of the sampling points approached unity during periods when elevated methylmercury concentrations were found, ***signifying the importance of groundwater recharge*** *in the MeHg generating process in this river. Although three major rain events early in the growing season led to pronounced but briefly elevated simulated tracer concentrations for interflow and* ***surface water runoff, these components were diluted and washed quickly downstream by groundwater recharge*** *when elevated MeHg concentrations were found in the river (Figs. 3 and 4)."[81] (Emphasis added)*

The fact is that groundwater provides much of the flow into wild rice waters, carries with it many nutrients, including dissolved sulfate and iron, and controls the chemistry of porewater in riparian environments. MPCA cannot ignore either the flow or, as will be seen below, the chemistry that accompanies the flow.

[81] Reference (17)

5.0 MPCA's key Hypothesis is not supported by the multiple lines of evidence

In a nutshell, MPCA's key hypothesis is that:

> ***<u>The source of sulfate is the water column.</u>*** *Sulfate from the water column migrates via chemical diffusion into the sediment and porewater. There, microbes convert sulfate to sulfide, using organic carbon in the porewater.* ***<u>The source of the organic carbon is the sediment</u>****. The* ***<u>sulfide</u>****, rather than sulfide,* ***<u>is the compound which is toxic to wild rice</u>*** *because "it is the porewater that is in contact with the roots of wild rice".*[82] *Iron reacts with the sulfide, providing some amelioration of the sulfide toxicity.* ***<u>The source of the sulfide is the sediment</u>****. Iron may ameliorate the toxicity of sulfide by precipitation it out of the porewater.* ***<u>The source of the iron is the sediment</u>****.*

Note that a **<u>hypothesis</u>** is not a fact or even a scientific theory:

> *"A* ***<u>supposition</u>*** *or proposed explanation* ***<u>made on the basis of limited evidence</u>*** *as a* ***<u>starting point</u>*** *for further investigation.*[83] (Emphasis added)

Berndt et al were studying the formation of methyl mercury (MeHg) in the St. Louis River. While not directly related to wild rice, the same processes are in place – sulfate is reduced to sulfide, using dissolved organic carbon, to form methyl mercury in the porewater. The formation of methyl mercury involves the same chemical and biological reactions in the sediment and porewater as does the formation of sulfide which can impact wild rice.

The work of Berndt et al suggests that, regarding sulfate from surface water interacting with sediment and porewater:

> *"****sulfate from mines [point discharges] may have had relatively little opportunity to interact with reduced sediments****.*[84] (Emphasis and brackets added)

> *"Two factors make it difficult for sulfate from the mines to impact MeHg in the rivers. First, the sulfate from mines is introduced largely as point sources at the ends of a relatively few tributaries and, thus, is limited geographically from interacting with riparian sediments in the great majority of the region. Second, even* ***<u>in the streams it flows through, it may be hydrologically excluded from reacting with riparian sediments that have the reduced conditions</u>*** *needed to promote methylation. The St. Louis River watershed receives, on average, approximately 8 inches more precipitation than is evaporated or transpired, and thus stream segments along the flow path mostly gain water from the surrounding landscape.* ***<u>The hydraulic gradient, is therefore, well poised to</u>***

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[82] Reference (2)

[83] Google dictionary at: https://www.google.com/search?sourceid=navclient&aq=&oq=hypothesis&ie=UTF-8&rlz=1T4IAGV_enUS652US653&q=hypothesis&gs_l=hp...0i131l3j0j0i131j41.0.0.0.1735...........0.LLx4jMLLz4k

[84] Reference (17)

produce and transport chemicals like DOC and MeHg to the river, but water derived from mines is not well poised hydrologically to interact with riparian sediments where DOC and MeHg are likely to be produced. *This does not mean that sulfate introduced as point sources from mines or municipalities will never impact zones of active mercury methylation, but it does imply that instances may be rare in a mining region that receives more rainfall than can evaporate or transpire from the landscape."*[85] (Emphasis added)

And

"However, the ***great majority of the mining sulfate added to streams apparently has little measureable impact on stream chemistry because opportunities are rare for the sulfate added as a point source to flow onto landscapes, through reduced soils, and back out into openly flowing waters****."*[86] (Emphasis added)

Ng et al also found that, except for flooding conditions, groundwater upwelling prevented influx of surface water.

"At our study site, very high concentrations of $SO2^{-4}$ from mining-derived surface water (2.8 to 10.3 mM) penetrates deeper into sediments under ***down welling flood conditions, while lower concentrations in the up-gradient groundwater buffer against the influx of surface water during upwelling conditions.****"*[87]

Thus, it is **unlikely** that sulfate from the water column is the main source for sulfide formation in the porewater. It is also **likely** that iron and dissolved carbon are migrating to the porewater, not from dissolution of the sediment (MPCA's primary source), but are being transported to the sediment, porewater, and ultimately, to the surface water body, via the groundwater flow into the wild rice water. MPCA presents no evidence that sulfate from the water column is the only source for conversion to sulfide in the porewater. It merely makes a policy decision, in the form of the hypothesis, that such is the fact.

In short, MPCA's hypothesis remains a "supposition" or "proposed explanation" – one that is not supported by a general understanding of what controls the chemistry of porewater. The hypothesis has led to a statistical analysis that lacks characterization of a potential controlling factor – groundwater quality. If the quality of groundwater controls porewater sulfide, instead of surface water sulfate (as assumed by the MPCA), this source may exist completely independent of surface water concentrations. It cannot be ruled out with the existing dataset. The likelihood, based on the work of Berndt et al., 2016 – that groundwater, rather than surface water, controls porewater sulfide in a wild rice bed means that controlling sulfate concentrations in overlying surface water may be ineffective in mitigating the effects of porewater sulfide. It means that changing surface water sulfate concentrations may not affect

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[85] Id.
[86] Id.
[87] Reference (37), page 18

concentrations of porewater sulfide **at all**. The lack of characterization, or inclusion of groundwater quality in this analysis leads to a proposed equation that is analogous to blaming increased incidents of drowning on ice cream consumption. This is unreasonable. MPCA's Unreasonable Weighting of Multiple Lines of Evidence

As noted above, MPCA relied primarily upon the following research which it commissioned to determine the toxicity of sulfate to wild rice plants:

- Controlled sulfate and sulfide toxicity experiments
- Outdoor container experiments
- Field Surveys of wild rice habitats [88]

However, MPCA unreasonably ignored research commissioned by the Chamber as well as other literature, giving all considerably less weight in its weighting of the multiple lines of evidence.

While MPCA concedes that sulfate in and of itself is not toxic to wild rice, MPCA next developed a hypothesis that sulfide in the rooting zone of wild rice was the toxicant which impacted wild rice, and that sulfate from the overlying porewater, diffusing into the rooting zone, was the primary source of that sulfide.

> *"MPCA staff had a **hypothesis**, … that sulfate exerts negative effects on wild rice when it is converted to hydrogen sulfide, which is much more toxic than sulfate. … the respiration of sulfate reducing bacteria in the sediment converts sulfate diffusing into the sediment from the overlying water into hydrogen sulfide in the sediment porewater."*[89]

> *"The sulfide concentration in the porewater, the water in the sediment between solid particles, is key because it is the porewater that is in contact with the roots of wild rice. The wild rice study and research supported the MPCA staff's hypothesis, showing that **the pollutant that harms wild rice is sulfide in the sediment porewater**."*[90] (Emphasis added)

MPCA's multiple lines of evidence do not prove MPCA's hypothesis; at best they demonstrate a correlation between sulfide and wild rice presence or absence. At worst, they demonstrate that a protective level of sulfide is much higher than proposed by the MPCA. Further, the MPCA has not resolved the conflicts between the findings of the hydroponic tests with the other studies it conducted. As such, it is unreasonable to propose such a low protective level, as will be seen.

[88] Chapter 1.A. of reference (2), page 4
[89] Section E.1. of reference (3), page 65
[90] Id

5.1 State-of-the-Art Controlled sulfate & sulfide toxicity experiments

MPCA effectively dismisses the very studies which represent the state-of-the art in toxicity testing, and the best controlled experiments. Pastor et al and Fort et al state-of-the-art controlled hydroponic studies clearly demonstrated that sulfate is not toxic to wild rice at concentrations observed in Minnesota wild rice waters. The studies also show that sulfide in the rooting zone (e.g. sediment and porewater) is not toxic to wild rice at concentrations observed in Minnesota wild rice waters. See above.

However, MPCA completely disregards the controlled, state-of-the-art toxicity testing for sulfate on wild rice, and effectively dismisses the Fort et al study on the toxicity of sulfide, despite the fact that it followed the recommendations of MPCA's Peer Review Panel. MPCA incorrectly calculates the toxicity of sulfide on the entire plant from Pastor et al, including those portions of the plant which are not and would never be exposed to anaerobic conditions or sulfide. MPCA disregarded the recommendations of its own Peer Review Panel, and did not require Pastor et al to perform new controlled sulfide toxicity tests, but incorrectly and unreasonably relied upon the flawed studies. MPCA appears to have purposely misinterpreted those tests, ignoring the results of the Fort et al tests and the recommendations of the peer review study.

Therefore, MPCA unreasonably relied upon the Pastor et al controlled sulfide toxicity tests (hydroponic tests) in, for example, Figure 1-2 of the TSD[91], and elsewhere throughout the SONAR and TSD.

5.2 Outdoor Container studies were seriously flawed and cannot be reasonably relied upon.

The MPCA unreasonably relied upon the data generated by Dr. Pastor et al in his outdoor container study. There are serious flaws in the outdoor container studies, because of which the MPCA should have not relied as heavily as it did in developing protective sulfide and sulfate levels.

Unlike the state-of-the-art controlled hydroponic tests conducted by Pastor et al and Fort et al, the outdoor container studies were much less well controlled. In direct contradiction to US EPA guidance, Pastor et al did not renew the solutions in the outdoor containers, resulting in depletion of iron, and perhaps nutrients and other compounds necessary for the growth and health of wild rice.

- Other serious flaws in the outdoor container study are:
- In 2013, 72 to 84% the control plants, for reasons unrelated to sulfate or sulfide concentrations;
- In the years following 2013, less than 30% of the plants survived, resulting in insufficient numbers for reasonable statistical analysis; and

[91] Chapter 1.C. of reference (2), page 34.

- Dr. Pastor et al failed to measure the initial concentrations of sulfide, iron, other nutrients and other parameters in the water, porewater and sediment, which could have resulted in depletion of iron and nutrients in the containers, which may have skewed the results of the studies.

The MPCA does not resolve the discrepancies between the results of the Fort et al controlled sulfate and sulfide toxicity testing, the Pastor et al controlled sulfate and (properly interpreted) sulfide toxicity testing and the uncontrolled outdoor container studies. These are significant as will be seen.

The Chamber noted these primary concerns with the outdoor container study in its 2014 Technical Analysis[92,93]

> *… it is not possible to know initial container conditions, including baseline sediment, porewater, and surface water physical conditions and chemical concentrations. Second, the containers are hydrologically isolated, preventing infusion of groundwater carrying iron or other constituents (e.g., plant micronutrients) that would be present in the natural environment. Nutrient depletion may also have occurred over time (without replenishment). Finally, in 2013, Dr. Pastor reported significant seedling mortality following thinning. As discussed by Dr. Pastor, seedling mortality may have been influenced by removal of five plants per tank in years 2011 and 2012 (one sixth of the population) resulting in depletion of the seed bank for future population growth.[94] In 2013, decreases in total plant biomass were not significantly correlated with increases in sulfate concentration.*

The 2013 data are particularly troublesome because many of the plants, including the controls, died. "In 2013, significant seedling mortality in all tanks after thinning but before the floating leaf stage precluded this sampling of individual plants".[95] The Chamber noted these deficiencies in its 2014 technical analysis and it bears repeating here.[96]

Unlike the hydroponic experiments conducted by Chamber and Fort Labs, no test acceptability criteria were established to determine whether the test data were acceptable. Therefore, these tests cannot be relied upon in determining or corroborating the level of sulfide which is protective of wild rice. In Dr. Pastor's other hydroponic toxicity experiments on sulfates, the following test acceptability criteria are established:

> *Tests were deemed acceptable if:*
>
> *1. At least 90% of control juvenile seedlings were living at test termination;*
>
> *2. Mesocotyl length of juvenile seedlings from control exposures were at least 5.0 cm at the end of the 10 day duration of growth; and*

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[92] Reference (24).
[93] Reference (47)
[94] Reference (25)
[95] Id.
[96] Reference (24).

3. Control juvenile seedlings did not indicate any visible phytotoxic or developmental symptoms at any time during the test and the controls grew. See Appendix 2 for more details.[97]

Dr. Pastor's sulfide hydroponic experiments had similar test acceptability criteria:

Tests were deemed acceptable using the same criteria as described above for the tests of sulfate on germination. See Appendix 3 for more details.[98]

The Fort Environmental Labs study applied more rigorous test acceptability criteria (Table 5):[99]

Table 5 Fort Labs Hydroponic Studies Acceptability Criteria

Criterion	Acceptable Limits	Criterion passed? (d 21 value, if applicable)
Control activation	95%	95%
Control mesocotyl emergence	≥30%	≥30%
Control survival	≥90%	≥90%
Positive control (BA) phytotoxicity	≥80%	≥80%
pH	6-7.5 in all replicates of control and treatments	6.5-7.0 in all replicates of control and treatments
Water temperature	21° ± 2°C (day), and nightly, 12 ± 2°C (night) in all replicates of control and treatments	21° ± 2°C (day), and nightly, 12 ± 2°C (night) in all replicates of control and treatments
Sulfate concentration	Inter-replicate CV ≤20% for control and treatments for individual measurement set (Study Day 0, 10, and 21)	Inter-replicate CV ≤20% for control and treatments based on TWA concentration and ≤35% 24-hour sulfide loss based on TWA concentration

No test acceptability criteria were established for the outdoor container studies.[100] Significant but undefined mortality occurred in 2013 across all concentrations, including controls. High mortality is indicative of a test system unable to support healthy plants absent the presence of the test variables (i.e., increased sulfate). In laboratories with established Quality Control and Quality Assurance programs, including laboratories which conduct Good Laboratory Practices studies whose data are used in regulatory applications, the results would subsequently be rejected as unreliable, especially given the poor rate of control survival (i.e., 15 percent in 2013). Under no circumstances should a test design that resulted in 85% control mortality be used to inform what might constitute a protective level of any potential

[97] Reference (26).
[98] Id.
[99] Reference (47).
[100] Reference (25).

pollutant. Although not directly applicable, an attempt was made to compare the results of the outdoor container study to the test acceptability criteria for the hydroponics study. That comparison is provided in Table 6.[101]

Table 6 Outdoor Container Study Acceptability Criteria[102]

Hydroponic Experiment Acceptability Criteria	Outdoor Container Study – Criteria Passed?
At least 90% of control juvenile seedlings were living at test termination	Fail – less than 15% of control seedlings survived
Length of juvenile seedlings from control exposures were at least 5.0 cm at the end of the 10 day duration of growth;	Passed. Initial seedling stem and leaf length was 6.1, 6.6 and 6.8 cm. Final control seedling stem and leaf length were 10.1, 11.4 and 12.9 cm
Control juvenile seedlings did not indicate any visible phytotoxic or developmental symptoms at any time during the test and the controls grew.	Passed in part, unknown in part. Control seedlings grew (see above). Phytotoxic or developmental symptoms of controls were not reported.

Based on Dr. Pastor's criteria for the hydroponic experiments, the outdoor container studies do not pass all test acceptability criteria.

It is important to note that control mortality at these levels (85%) represents a stressed population of wild rice, and the impact from any added stressors are likely to be greatly exaggerated compared to a healthy population of wild rice.

Because the 2013 "crop" was so poor, there were ramifications for the 2014 and 2015 years. No changes were made to the outdoor containers following the across-the-board mortality in 2013. Pastor et al note:

> "The rate of decline in seedling survival with amended sulfate was twice as high in 2014 and 2015 than in 2012 and 2013."[103]

This is hardly surprising, and it cannot be determined whether the trend begun in 2011 continues, or whether the decline in seedling survival is due to the unknown factors that caused the across-the-board mortality observed in 2013. Although Pastor et al opine:

> "We believe this early season mortality was due to a record cold and late spring in northern Minnesota in April and May of 2013; ice stayed on lakes an average of 3 weeks later than the median ice-out date (data available online)."[104]

While this may have been the case, it may also have been due to depletion of any number of parameters (e.g. iron, nutrients) which affected wild rice plants in the control containers as well as the treated

[101] Reference (26)
[102] Id.
[103] Reference (1)
[104] Id.

containers. It may have been disease, or another parameter that was not measured. It is impossible to tell, and the outdoor container studies should have been given no weight, given the across-the-board mortality observed.

Myrbo et al admit as much:

> "This experiment was not an accurate long-term mimic of the consequences of increased SO4 loading on net porewater sulfide concentrations, because the external supply of Fe was cut off at the inception of the experiment. With no loading of Fe, **<u>the continued production of sulfide could eventually consume all available Fe, allowing sulfide levels to exceed those observed in a natural system at equivalent surface water SO4 concentrations</u>**. This mesocosm experiment provides evidence for just such a process. The experiment was continued for two years after the synoptic sampling presented here. In August 2015 porewater sulfide was much greater than had been observed in 2013, and disproportionately so in the highest SO4 treatment. Between the 2013 and 2015, porewater sulfide increased in the control SO4 treatment (about 7 mg SO4 L-1) from a median value of 68 µg L-1 in 2013 to 116 µg L-1 in 2015, a 1.7x increase. Porewater sulfide in the highest treatment (nominally 300 mg SO4 L-1, Table 3) increased from a median value of 808 in 2013 to 9,350 µg L-1 in 2015, an 11x increase [Pastor et al., 2017]. In a survey of 108 Minnesota waterbodies, only two exceeded a porewater sulfide level of 3,200 µg L-1 [Myrbo et al., submitted].[105] (Emphasis added)

Myrbo also advises caution in using the results of the outdoor container studies:

> "Although **<u>caution should be used</u>** **<u>in extrapolating the results of the mesocosms to natural systems with continuous carbon and iron loads</u>**, the results presented here clearly demonstrate the consequences of increased SO4 concentrations that enhance MSR-driven mineralization of organic matter, as well as the impact of elevated sulfide on wild rice [Pastor et al., 2017]."[106] (Emphasis added)

The test design did not include regular changing of the solutions in the containers, as suggested in US EPA guidance. While some rainwater and groundwater was added to the system,[107] the tests were essentially static tests. ASTM international and US EPA recommend that static tests be limited to no longer than 96 hours[108], and if test water is to be renewed, it should be renewed "once every 24 h, either by transferring the organisms from one test chamber to another or by replacing nearly all the test solution."[109]

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[105] Reference (38)
[106] Id
[107] Id at 24
[108] Reference (12)
[109] Id.

Thus, the outdoor container tests conducted by Pastor et al did not follow US EPA guidance, and should be given considerably less weight.

While the water levels were maintained by intermittent additions of well water or precipitation, no additional nutrients or sulfate was added, and the water quality was infrequently monitored. This well water is ground water from an aquifer which does not have the same chemical composition as shallow groundwater that would be in contact with water bodies in nature. Without nutrient and iron-infused recharge, this experimental design more closely resembles a seasonal pond or pothole, where wild rice may not grow or grow as well as in a natural setting. The test design likely stressed the entire wild rice population and made the results questionable. Conditions with no groundwater infusion, and no inflow or outflow carrying additional nutrients are important constraints that confounded results. Given these confounding results, the outdoor container tests should not be relied upon in revising the water quality standards.

It appears that the tanks were nutrient deficient including iron and perhaps other limiting trace metal nutrients. As discussed by Dr. Johnson, in hydrologically isolated outdoor containers without the delivery of iron, it is likely that sulfide would build up.[110] Without the benefit of measurements of initial conditions and data from previous years' experiments, no one can analyze the 2013 results. Similarly, without the benefits of measurements of initial conditions, no one can determine whether sulfide build up (unprecipitated by iron) that occurred or other substances (or lack of other substances) affected the test organisms. It may be that the third year of testing (2013) was a part of the normal life cycle of wild rice. Dr. Pastor notes (reference (2)):

> *Delays in the release of nitrogen from these litters in subsequent years may be responsible for the population oscillations of 3-5 year periods often seen in wild populations (Pastor and Walker 2006, Walker et al. 2010, Hildebrandt et al. 2012).*

The Great Lakes Indian Fish and Wildlife Commission also notes, based upon years of observations of wild rice;

> *Rice abundance can vary widely from year to year, especially on the most "lake-like" beds. The rule-of- thumb for lake beds: A typical four year period will include a bumper year, two fair years, and a bust year*.[111]

The results between 2013 and 2015 may have been simply part of the natural low-density cycle of wild rice, caused, perhaps, by delays in release of nutrients from the litter.

Based on all of these considerations, outdoor container study should not be relied upon to inform or develop water quality regulations.

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[110] Reference (39)
[111] Reference (28)

The Peer Review Panel also expressed criticism about the outdoor container studies (Reference (11)). The panel had the following recommendations regarding the outdoor container studies:

- The performance of wild rice and water quality conditions in the controls need to be **compared to that expected under natural conditions** in order to validate the test systems themselves.
- Clarity regarding the measured responses should be improved; for example, when, how, and why responses occurred should be described in the report.
- Plant responses as they relate **to measured, not nominal, sulfate concentrations** should be described and modeled.
- The demographic data should be used to develop a population model in order to understand factors influencing population persistence, within the limits of the study conducted. This should help elucidate whether specific measured responses can be linked to population persistence, which could inform assessment endpoints for field monitoring.
- Plant responses as they relate to measured porewater sulfide concentrations should be modeled, similar to what is recommended above.
- If possible, the **mesocosm study should be repeated** with an **effective control for sulfate**, and with **more treatment levels bracketing the current water quality standard**. This could be achieved by reducing replication, but should be done with caution following power analysis.
- Other, more powerful statistical approaches, for example, mixed-level (hierarchical) modeling, should be explored when analyzing the totality of the dataset.
- **Rooting zone profiles should be incorporated** into the interpretation of plant response data. (Emphasis added)

Given the serious flaws in the outdoor container data and corresponding Peer Review Panel criticisms, the MPCA cannot reasonably rely upon the results to corroborate a “protective” sulfide” or “protective sulfate” level.

MPCA does not reconcile the differences between the “protective” sulfide levels determined from the hydroponic studies and the outdoor container studies. In Figure 1.2 of the Technical Support Document, MPCA provides the following EC10 values:

Study/Experiment	EC10 Value (µg/L)
Pastor et al hydroponic (avg. Initial concentration) *	251
Pastor et al hydroponic (time weighted arithmetic avg)	106
Pastor et al hydroponic (time weighted geometric avg) (1)	39
Fort et al hydroponic (lowest EC10 level) (1)	936

(1) Estimates marked with an asterisk (*) are identified in the text as deserving less weight in the weighing of multiple lines of evidence. [112]

If in fact the MPCA had looked at the effect of sulfide **in the rooting zone** from Pastor et al, as discussed above, a 4th EC10 value could be calculated:

Study/Experiment	EC10 Value (µg/L)
Pastor et al hydroponic (avg. Initial concentration) *	251
Pastor et al hydroponic (time weighted arithmetic avg)	106
Pastor et al hydroponic (time weighted geometric avg) *	39
Pastor et al hydroponic (effects in rooting zone only) (1)	819
Fort et al hydroponic (lowest EC10 level) (1)	936

(1) Estimates marked with an asterisk (*) are identified in the text as deserving less weight in the weighing of multiple lines of evidence. [113]

While MPCA cites the Peer Review Panel comments as the reason to reject the average initial concentration value of 251 µg/L (because sulfide levels fell throughout the experiment because the growth solution was not renewed, per US EPA guidance), the MPCA does not calculate the impact on those parts of the wild rice plant in the rooting zone and expected to be exposed to sulfide. Again the results of the Pastor et al hydroponic studies, when reasonably focused on those parts of the plant that are in the rooting zone and the Fort et al hydroponic studies show good agreement. MPCA does not resolve the very large discrepancies between the results of the controlled hydroponic studies and the outdoor container or field survey studies.

MPCA makes the policy decision that the Fort et al studies are "deserving less weight, even though that study followed all of the recommendations of the Peer Review Panel (not just the one which the MPCA made a policy decision to use), and which followed the US EPA guidance on conduct of toxicity testing, and which met the standards for Good Laboratory practices.

MPCA made the policy decision:

> *"under natural conditions 21-day old wild rice plants would not have access to the atmosphere because the seeds germinate in water that is much deeper than 1 cm, and the stems would not yet have elongated sufficiently to reach the water surface."*[114]

[112] Chapter 1.C. of reference (2), page 32.
[113] Chapter 1.C. of reference (2), page 32.
[114] Chapter 1.C. of reference (2), page 38

In fact, a careful review of the methods used by Fort et al, shows that a consistent anaerobic condition was made up to the water level (by bubbling nitrogen gas through the growth medium, resulting in a well-mixed medium and maintaining a much more constant level of sulfide than did Pastor et al. MPCA also makes the policy decision to ignore the fact that once the wild rice plant rises above the sediment, there is sufficient oxygen dissolved in the water:

> *"… the availability of oxygen in water (a maximum of about 10 ppm)"*[115]

MPCA also makes the policy decision to ignore the fact that the plant will photosynthesize while underwater and produce oxygen by themselves:

> *"Because the plants were photosynthesizing and producing oxygen, the sulfide concentration declined during these two‑three day periods."*[116]

Thus, MPCA unreasonably rejects the Fort et al sulfide hydroponic studies, misinterprets the Pastor et al sulfide hydroponic studies, and does not reconcile the fact that there is nearly a factor of 10 difference between these studies and the other studies on which the MPCA relies.

5.3 Field Surveys were seriously confounded

MPCA relies most heavily on the field surveys to determine a "protective" concentration of sulfide in the porewater, and the "protective" concentration of sulfate in the water column. Three of the six studies which MPCA fully relied upon (and did not make the policy decision that the others were "deserving less weight"). Yet the field surveys contain serious flaws, which make it unreasonable for the MPCA to so heavily rely upon them.

Unlike the state-of-the-art controlled hydroponic studies, the field surveys are entirely uncontrolled. The wild rice growing in the wild rice waters (and non-wild rice waters) surveyed were subject to weather and all of the other stressors which can affect the presence and density of wild rice (the only two biological parameters that the MPCA measured for wild rice). MPCA acknowledges that several of these other stressors are "statistically significant", yet does nothing to separate their effects from the effects of sulfide. Instead, MPCA ascribes all ill effects on wild rice to sulfide and sulfide alone.

Other major flaws include the following:

- MPCA unreasonably used data from non-wild rice waters to determine "protective" levels of sulfide and sulfate
    - MPCA admitted as much during Dr. Swain's testimony at the first of several hearings on the proposed rule:

[115] Id.
[116] Reference (13)

"The point of the equation is to relate sulfate to sulfide given the amount of iron and carbon at a particular site. And it's a chemical relationship, it doesn't matter whether there's wild rice there or not. So, in calculating the equation, we include sites with no wild rice because it's the chemistry that we're performing statistics on."[117]

And

"The error rates we've been discussing are how accurately the sulfide concentration is predicted and has nothing to do with wild rice presence and absence, I agree."[118]

- MPCA ignores other stressors of wild rice, several of which the MPCA determined were statistically significant, in determining the sulfide and sulfide alone impacts the growth and density of wild rice
- MPCA does not prove its hypothesis, in that there is no causal determination that sulfide in the porewater (e.g. the rooting zone) impacts the presence and density of wild rice
- MPCA does not resolve the inconsistencies between the results of the hydroponic studies (where only sulfide or sulfate are stressing the wild rice) and the field surveys, where multiple stressors are operating on the wild rice.

5.3.1 Use of non-wild rice waters to determine "protective" levels of sulfide and sulfate

MPCA claims that waters that contain white water lilies (*Nymphaea odorata*) and yellow water lilies (*Nuphar lutea*) indicate that wild rice "would most likely grow":

*"**When the field crews could not find wild rice** in a waterbody, **they sampled the water and sediment at a location where wild rice would most likely be growing** if it were to grow in that waterbody. These **"non-wild rice" sampling locations were usually identified by the presence of either white or yellow waterlilies. The presence of waterlilies is taken to indicate that the habitat is similar to the habitat required by wild rice**, because waterlilies and wild rice frequently co-occur (Pillsbury and McGuire, 2009). In addition, in an analysis of 1,753 MDNR aquatic plant surveys from shallow Minnesota lakes, the odds of finding wild rice where there are water lilies are 27 times the odds of finding wild rice where there are no water lilies, with a 95% confidence interval of 20-36 times. This high odds ratio is strong evidence that wild rice and waterlilies share many habitat requirements, although it appears that waterlilies may have a higher tolerance to elevated sulfide concentrations."*[119] *(Emphasis added)*

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[117] Transcript, State Of Minnesota Office Of Administrative Hearings For The Minnesota Pollution Control Agency MPCA Proposed Amendment Of The Sulfate Water Quality Standard Applicable To Wild Rice And Identification Of Wild Rice Waters OAH Docket No. 80-9003-34519, Revisor No. RD4324A, Kirby Kennedy & Associates, wq-rule4-15y, Page 148 Lines 15 to 23,

[118] Id at Page 152 Lines 22 to 25

[119] Chapter 1.A. of reference (2), page 8.

Note that MPCA cites only two supporting pieces of information. One of them – "an analysis of 1,753 MDNR aquatic plant surveys from shallow Minnesota lakes"[120] – appears to be an unpublished analysis of unpublished data. MPCA provides no citation to either. This is clearly not in conformance with US EPA guidance:

> *"All data that are used should be available in typed, dated, and signed hard copy (publication, manuscript, letter, memorandum, etc.) with enough supporting information to indicate that acceptable test procedures were used and that the results are probably reliable. In some cases it may be appropriate to obtain additional written information from the investigator, if possible.* ***Information that is confidential or privileged or otherwise not available for distribution should not be used****."[121] (Emphasis added)*

It is also clearly not in conformance with the Minnesota Administrative Rules which provide, in applicable part:

> *"The statement must include:*
>
> *A. citations to any economic, scientific, or other manuals or treatises the agency anticipates relying on;"[122]*

MPCA appears to be relying upon the analysis of the DNR data. The SONAR (the TSD is Exhibit 1 to the SONAR) clearly does not supply any required citation.

The other piece of information is the publication by Pillsbury et al.[123] Those authors provide the following insights:

> "Plants closely associated with high and medium wild rice stands included *Potamogeton natans*, *Nymphaea odorata*, *P. foliosis*, *Lemna trisulca*, and *P. richardsonii* (Figure 1a). These *Zizania*-associated macrophytes **may** be tolerant of the shaded conditions produced by emergent Zizania stalks and leaves, and might also benefit from increased protection from wind and waves within these stands.[124] (Emphasis added)
>
> "**Plants that did not have a close association with wild rice** wetlands included *Elodea canadensis*, ***Nuphar variegata***, filamentous green algae (*Zygnematales*), *Utricularia vulgaris*, *Sparganium eurycarpum*, *Najas flexilis*, and *Potamogeton robbinsii* (Figure 1a). Many of these plants **may not grow well inside dense wild rice stands** due to excessive shading."[125] (Emphasis added)

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[120] Id
[121] [121] Reference (4)
[122] Minn. R. 1400.2070, Subp.1
[123] Reference (29)
[124] Id.
[125] Id.

> "***Nuphar variegata*** and *U. vulgaris* **are associated with high and medium density rice wetlands in the adjacent site ordination** and low density wetlands with the within-rice ordination (Figures 1a and b). This pattern suggests that without the presence of rice, these plants prefer environmental conditions similar to optimal rice conditions (indicating a possible competitor). This agrees with Vennum (1988) who noted that *Utricularia macrorhiza* was often adjacent to wild rice stands in Minnesota. Meeker (2002) conducted **competition experiments with *Nuphar variegata* that demonstrated a loss in wild rice survivorship**. Lee (1986) found that **plant competition (based on non-rice plant densities) explained a significant amount of variation in wild rice density** after a large seeding effort in Oval Lake, Ontario.
>
> Resource managers often cite **direct competition** with other aquatic plants, such as cattails (*Typha spp*.), pickerelweed (*Pontederia cordata L*.), or waterlilies (*Nymphaea and Nuphar*) **as a major factor in the disappearance of wild rice stands**. However this hypothesis has rarely been tested."[126] (Emphasis added)

This citation hardly constitutes proof that water lilies indicate that wild rice would "most likely be growing". The authors first cite only an association, not any biological reasons why water lilies and wild rice should cohabit the same area. Second, yellow water lilies do not grow in the same area as wild rice, merely adjacent to it. Third, it may be that in the water tested that the water lilies have outcompeted the wild rice, perhaps due to development, and that the site is no longer conducive to wild rice growth.

It is curious that allow the MPCA feels strongly enough about the presence of water lilies to use data from waters where only water lilies (and not wild rice) grow to develop a "protective" sulfide level, yet the MPCA has not listed those waters as wild rice waters.

MPCA cannot have it both ways. Either the waters which contain water lilies only should be listed as wild rice waters, or they should be excluded from the analysis. Given the fact that the two lines of evidence upon which the MPCA relies are either unpublished (in clear violation of US EPA Guidance and Minnesota rules) or associative at best, MPCA unreasonably included waters in which only water lilies (and not wild rice grew).

5.3.2 Ignoring other stressors of wild rice

MPCA admits that a number of factors, other than sulfide or sulfate, can stress wild rice and inhibit its growth. Table 1-3 "Correlations of field variables with wild rice and porewater sulfide"[127] lists the following additional parameters (beyond porewater sulfide), that are significantly correlated with wild rice growth:

- Porewater potassium (PW K)

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[126] Id.
[127] Reference (2)

- Water depth (m)
- Water Transparency (cm)
- Surface water nitrogen (SW N)
- Sediment Selenium (% dry) (Sed Se)
- Surface water temperature (SW Temp)
- Porewater Iron (PW Fe)
- Surface water pH (SW pH)
- Surface water phosphorus (SW P)
- Latitude
- Sediment Total Sulfur (Sed TS)

States and tribal governments who restore wild rice list additional significant stressors of wild rice:

- Water level fluctuations
  - Natural seasonal fluctuations
  - Influences of beaver dams
- Invasive species
  - cattail, purple loosestrife, and Eurasian watermilfoil
  - carp
- Competitive plants (see above discussion)
- Motorized boat limitations and/or no wake zones during floating leaf stage[128]

Yet the MPCA unreasonably and single-mindedly focuses on sulfide as the one causative factor for the health and growth of wild rice. The correlations developed by the MPCA are unreasonable, as they do not take into consideration statistically significant and long known factors other than sulfide which affects the growth and health of wild rice.

[128] References (28), (29), (30), (47)

5.4 MPCA does not resolve the inconsistencies between the multiple lines of evidence

The hydroponic studies (properly interpreting the Pastor et al work to look at effects on only those parts of the wild rice plant in the sediment), show that sulfide is not toxic to wild rice at levels below 2,880 to 3,200 μg/L. The statistical analysis of the field survey data purport to show a "protective" sulfide level of 120 μg/L – more than a factor of 10 lower. The hydroponic studies, conducted in accordance with US EPA guidance, with sufficient controls in place and sufficient elimination of other confounding stressors, clearly demonstrated that sulfate and sulfide, in and of themselves, are not toxic to wild rice at concentrations not typically seen in Minnesota wild rice waters.

In stark contrast, the analyses of the field surveys, which are advised against in US EPA guidance, and which have no controls in place and which include the influence of myriad, statistically significant confounding stressors, shows a "protective" sulfide level of only 120 μg/L.

MPCA needs to reconcile the 10-fold difference between the "protective" sulfide levels determined in its analysis of the field surveys and the hydroponic studies which controlled all of the other myriad statistically significant confounding stressors.

It is likely that if MPCA used **only those waters which actually are listed wild rice waters**, and used the "protective" sulfide levels from the hydroponic studies, that the calculated "protective" sulfate level would be in line with the measured hydroponic sulfate levels.

MPCA needs to explain the large differences between the proposed "protective" sulfide level and "protective" sulfate level derived from that sulfide level, and the actual toxicity of sulfate to the wild rice plants or sulfide to those portions of the wild rice plants in the root zone (e.g. the sediment in contact with the porewater). Considering that the hydroponic studies were conducted in accordance with US EPA guidance and employed state-of-the-art toxicity testing procedures, and that the field surveys are fraught with the very issues with which the US EPA cautions against their use, MPCA needs to give a much higher weight to the hydroponic studies, and weight them at least as highly, if not higher, than the field surveys.

6.0 MPCA did not adequately consider the costs to comply with the proposed rule

6.1 The cost to comply with this standard is "prohibitively expensive"

The MPCA in the SONAR admits that the costs to reduce sulfate in discharges from municipalities and industry are "prohibitively expensive".

On page 107:

> "In the case of wild rice and sulfate, the MPCA recognizes that **sulfate treatment is currently prohibitively expensive** for many dischargers, and therefore when the proposed rule revisions are adopted, dischargers (industrial and municipal) may apply for variances from the standard until economically feasible treatment systems can be designed and constructed."[129] (Emphasis added)

At page 182:

> "Treatment for sulfate removal can be **extremely expensive**. As discussed above, there are few options for sulfate removal, with RO/membrane filtration being the most reliable method for effectively removing sulfate from wastewater discharges."[130] (Emphasis added)

And at page 184:

> "Membrane treatment with evaporation and crystallization also has **significant secondary costs** such as high-energy requirements leading to high carbon emissions, advanced operator training requirements and an increased need for operator labor hours. The combination of these secondary considerations could prove **prohibitively burdensome for affected communities**."[131] (Emphasis added)

Although MPCA notes that it intends to grant variances "until economically feasible treatment systems can be designed and constructed",[132] the only technology that can effectively remove sulfate to the levels required under the proposed rule is membrane filtration – nanofiltration or reverse osmosis. MPCA explains the operation and costs of reverse osmosis in the SONAR at pages 178 to 181.

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[129] Reference (3), page 107.
[130] Reference (3), page 182
[131] Reference (3), page 184
[132] Reference (3), page 107

6.2 For cities, annual costs can exceed $1 million/year

For cities, capital costs can range from $10 million to over $50 million (depending upon flows and concentrations)

MPCA's Draft Cost Analysis [133] determined that the annual operation and maintenance costs ranged from $500,000/year to nearly $1 million/year, depending upon flow rates, initial sulfate concentrations and the "protective" sulfate concentration. The majority of the operation and maintenance cost is energy cost to evaporate and crystallize the salts removed.

Combining the annualized capital costs with the annual operation and maintenance costs yield an annualized cost of over $1 million/ year for a 1 million gallon/day city.[134] Assuming 100gallons/person/day[135], a 1 million gallon/day city would have a population of 10,000, about the size of the cities of Fairmont or Grand Rapids.[136] For the City of Fairmont, the number of households is 4,793.[137] A cost of $1 million amounts to $209/year per household. For the city of Grand Rapids, the number of households is 4,996[138]. A cost of $1 million amounts to $200/year per household.

The median household income for Martin County, in which the city of Fairmont is located, is $8,831.[139] The median household income for Itasca County, in which the city of Grand Rapids is located is $18,965.[140] MPCA, quoting the Minnesota Public Facilities Authority (PFA), lists a 1.4% "benchmark for combined capital and operation & maintenance costs of an "affordable" wastewater infrastructure".[141] For the city of Fairmont, an affordable annual cost would be 1.4% x $8,831 = $123/year, about ½ of what a membrane treatment system would cost. For the city of Grand Rapids, an affordable annual cost would be 1.4% x $18,965 = $265, about what a membrane system would cost.

However, these costs are over and above the current treatment costs which those cities face, so these costs, on top of the current wastewater charges, would be clearly not "affordable". And, at the December 2016 MPCA Wild Rice Advisory Committee meeting, the MPCA admitted that the cost estimates presented in MPCA's Draft Cost Analysis Components of Regulatory Analysis Proposed Sulfate Standard for Protection of Wild Rice December 2016[142] may be low by a factor of two. Thus, these costs are more than twice what these cities could reasonably afford.

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[133] Reference (34)Table 9 of Reference (34), page 25
[134] Table 10 of Reference (34), page 26
[135] Reference (35)
[136] Minnesota Cities by Population, Minnesota Demographer at https://www.minnesota-demographics.com/cities_by_population
[137] Minnesota State Demographic Center, Population Finder for Cities and Townships at https://mn.gov/admin/demography/data-by-topic/population-data/our-estimates/pop-finder2.jsp
[138] Id.
[139] US Census Bureau, MEDIAN INCOME IN THE PAST 12 MONTHS (IN 2015 INFLATION-ADJUSTED DOLLARS) more information 2011-2015 American Community Survey 5-Year Estimates at https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?src=bkmk Note that median household income is only available at the county level, not at the city level.
[140] Id
[141] Chart 13 of reference (33), page 17.
[142] MPCA presentation at the December 2016 Wild Rice Advisory Committee Meeting, Duluth, MN

6.3 For Industry, costs are even higher, especially taconite processors

For industry, because flows are generally higher and sulfate concentrations are higher than municipal wastewater, costs are even more "prohibitive". For taconite mines and processing plants, there are multiple discharge points and multiple sources of sulfate, including scrubbers, mines and waste rock piles, tailings basin, as well as rainfall over the vast areas which encompass a taconite mine and plant.

MPCA estimates a net present value of $62.5 million to treat a single discharge from a taconite plant.[143] This includes capital costs of $21 million and annual O&M costs of $2.8 million/year. Note that this is for a single discharge at a facility which have multiple discharges (e.g. from mines, tailings basins, processing plants). Such costs are in addition to additional costs taconite plants are facing to meet the MPCA's mercury TMDL[144], which are additional millions in capital costs and millions/year in operation and maintenance costs.

Again, as noted above MPCA admits that its cost estimates may be low by a factor of 2[145].

[143] Table 11 of Reference (34), page 25
[144] Chapter 4 of reference (36), page 9
[145] MPCA statements at the December 2015 Wild Rice Advisory Committee Meeting.

7.0 Summary

While MPCA's use of multiple lines of evidence, and the use of US EPA's "weight of evidence" guidance may be reasonable, there are fundamental problems with both the underlying evidence and with MPCA's policy decisions on weighting the relative value of each line of evidence.

7.1 MPCA's model and Key Hypothesis are incorrect and not supported by the evidence

First, MPCA's model is unreasonable in that it paints all wild rice waters as essentially bathtubs, with no interaction between the surface water, sediment and groundwater, when multiple lines of research show that the groundwater may be the source of the very compounds which may influence the formation of sulfide, and its effect upon wild rice. Sulfate, iron and organic carbon are brought into the sediment and water column with groundwater discharging into the surface water. At least one researcher has noted that wild rice prefers locations of groundwater inflow.[146]

Second MPCA's model is unreasonable in that it assumes that all sulfate migrates to the sediment from the water column, and that all dissolved iron and organic carbon in the porewater (root zone) comes from the sediment. Dissolved iron and organic carbon could just as easily migrate from the water column to the sediment and porewater, and from the groundwater to the sediment and porewater. Research has shown that, in fact, groundwater is the more likely source of all of these compounds. MPCA unreasonably ignores the potential contribution of these migrations, and unreasonably relies upon an overly-simplified model to determine the "protective" level of sulfide and sulfate.

7.2 Multiple Lines of Evidence were incorrectly and unreasonably relied upon

7.2.1 Hydroponic data

Using the standard, hydroponic toxicity tests per US EPA guidance, sulfate is not toxic to wild rice at concentrations well above the concentrations seen in MN wild rice waters. Therefore, the current standard of 10 mg/L sulfate has no scientific validity. The mode of action of sulfate is also now well understood – it, like other salts, exerts osmotic pressure on the plant, and is no more toxic than any other salt. Therefore, there is no need for a "protective" sulfate standard.

Similarly, based on the effects of sulfide on the rooting zone (and those portions of the plant in the sediment and exposed to the porewater), sulfide is not toxic to wild rice at concentrations seen in most Minnesota wild rice waters. While the mode of action is not well understood at this point, it is clear from these experiments, un-confounded by other wild rice stressors, that sulfide is not toxic to wild rice at concentrations seen in Minnesota wild rice waters. Therefore there is no need for a "protective" sulfide standard.

[146] Reference (22)

7.2.2 Outdoor Container studies

There were serious issues with the outdoor container studies conducted by Pastor et al. The outdoor containers were, in fact, "bathtubs" which had no interaction with the groundwater. The solutions were not replenished, per US EPA guidelines, and so critical nutrients, not least iron, were depleted. Other nutrients or critical elements may also have been depleted, as 85% of the plants, including controls, died in year three of the five year study. Results from years 4 and 5 were also characterized by poor wild rice growth. As a result, the outdoor container study did not meet Good Laboratory Practices, nor did it conform to US EPA guidance. MPCA was unreasonable when it relied upon the outdoor container study results in determining the "protective" level of sulfide.

7.2.3 Field Surveys

The field surveys suffered from very shortcomings for which US EPA guidance cautions against its use: many confounding factors make it difficult, if not impossible, to isolate the impact of a single stressor (e.g. sulfide) on the growth and health of wild rice. MPCA admits that there are multiple statistically significant other stressors which impact the presence and density of wild rice, and MPCA made no effort to sort out the impacts from these other stressors. Rather, MPCA blithely ignored their impacts, and ascribed all deleterious wild rice impacts to sulfide and sulfide alone. This is unreasonable and MPCA should not have relied on the field surveys in developing a "protective" sulfide level.

The field surveys were also confounded by the fact that MPCA unreasonably included waters which are not wild rice in determining a "protective" level of sulfide to protect wild rice. Again, MPCA cannot have it both ways – those waters which are not listed as wild rice waters should have been excluded from the analysis. As the purpose of the standard is to protect the "the harvest and use of grains from this plant serve as a food source for wildlife and humans"[147], MPCA unreasonably included waters which do not produce wild rice for "harvest and use" and which are not protected for such uses.

Because of these significant shortcomings, because MPCA cannot reasonably ascribe all deleterious effects on wild rice to sulfide, MPCA unreasonably relied upon the field surveys in developing a "protective" sulfide level.

Thus, only the hydroponic studies are able to show the impacts of sulfate and sulfide on wild rice, without either other confounding stressors (e.g. the field surveys) or depletion of iron and other critical growth factors (e.g. the outdoor container studies). MPCA unreasonably relied upon the field surveys and outdoor container studies, and unreasonably denigrated the hydroponic studies in determining "protective" levels of sulfide and sulfate.

The hydroponic studies clearly show that neither sulfate nor sulfide are toxic to wild rice at concentrations seen in Minnesota wild rice waters. Therefore, MPCA has not demonstrated that there is a need for

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[147] Chapter 1.D. of reference (3), page 13

"protective" levels of either sulfide or sulfate to protect the use of "the harvest and use of grains from this plant serve as a food source for wildlife and humans".

7.3 MPCA is lacking critical evidence "connecting the dots"

While MPCA has spent over $1.5 million on research, and other entities (e.g. the MN Chamber of Commerce) have spent additional monies, the results are, at best, inconsistent. The state-of-the-art controlled tests clearly show that neither sulfate nor sulfide are toxic to wild rice at concentrations observed in Minnesota wild rice waters. While MPCA conducts a series of statistical analyses to allegedly show that a "protective" sulfide in porewater standard is needed, both the underlying data and the statistical analysis are fraught with errors, and contradicted by the literature. The result is an inconsistent body of evidence, some of which shows that a sulfide in porewater and sulfate in the water column water quality standard may be necessary, and other showing that such standards are neither needed nor reasonable.

Even if we accept for the moment, MPCA's conclusions that a porewater sulfide and water column sulfate "protective" water quality standard is needed, MPCA has failed to present evidence to show that making the changes which such water quality standards will actually result in protection of the beneficial use – "the use of the wild rice grain as a food source for wildlife and humans".[148]

For example, the MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in discharges to surface waters will effectively reduce sulfide in the porewater in wild rice waters. Indeed, Berndt et al[149] reach an entirely opposite conclusion.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in the water column will better protect wild rice. None of the controlled hydroponic studies show any evidence for this, nor do the outdoor container studies nor do the field surveys. Again, Berndt et al [150]shows that sulfate in the surface water has little to do with sulfate reduction in the sediment, while groundwater flow provides the bulk of flow as well as sulfate, organic carbon and iron in the sediment.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfate in the water column will reduce sulfide in the porewater. This was simply not tested in any of the studies, nor in any of the literature cited by the MPCA. Yet the proposed rule explicitly says that this is what needs to happen to comply with the rule. In wild rice waters where the porewater sulfide exceeds the protective level, dischargers of sulfate will need to reduce their discharges of sulfate. Yet there is no evidence that reducing sulfate in discharges will result in significant reductions in water column sulfate, or that reducing sulfate in the water column will reduce sulfide in the porewater. Considering that cities and industries may be required to expend billions of dollars to reduce sulfate in their discharges, through the use of membrane filtration treatment, MPCA should be able to solidly demonstrate, in at least one wild rice

[148] Reference (3) page 14
[149] Reference (17)
[150] Id.

water, that reduction in sulfate results in reduction in porewater sulfide. MPCA has not done so, and thus the proposed rules are unreasonable.

MPCA has not and cannot provide any studies, literature or other evidence that reducing sulfide in the porewater will better protect wild rice. While MPCA has presented a statistical analysis of field survey data to show that sulfide may be toxic to wild rice at levels above 120 µg/L, MPCA can point to no test, no literature nor any other piece of evidence that shows that a wild rice water with high porewater sulfide had wild rice presence or density restored by reducing sulfide in the porewater. Again, given the "prohibitively expensive" (MPCA's own words) costs to reduce sulfate in discharges will result in reduced porewater sulfide, or that reduced porewater sulfide will result in the presence or increased density or health of wild rice.

Therefore, the "prohibitively expensive" costs to comply with the proposed rule may provide no additional protection for wild rice. MPCA has not and cannot provide any studies, literature or other evidence that these "prohibitively expensive" costs will have any positive impacts on wild rice.

7.4 The Cost to comply with the proposed rule is "prohibitively expensive"

MPCA admits that the costs to comply with the proposed rule is "prohibitively expensive". The only technology that can achieve the low levels required by the proposed rule is membrane treatment – nanofiltration or reverse osmosis. There are no other technologies on the horizon that can remove +2 anions at a reduced cost. Coupled with the lack of evidence, as noted above, that reducing sulfate in discharges from municipal and industrial sources will affect the water column sulfate concentration, the porewater sulfide concentration, or have any effect on wild rice, such "prohibitive" costs are unreasonable.

8.0 Recommendations

We respectfully request that the current sulfate standard of 10 mg/L[151] be eliminated, as the weight of evidence clearly shows that sulfate is not toxic to wild rice at that concentration or at any other concentration observed in Minnesota wild rice waters.

We respectfully request that the rule be remanded to the MPCA, to address the errors, uncertainties and inconsistencies noted above, particularly the inconsistency that multiple studies show that concentrations of sulfate and sulfide are not toxic to wild rice at concentrations observed in Minnesota wild rice waters, while other studies show that a “protective” concentration of 120 µg/L, and a “protective” concentration of sulfate, which are orders of magnitude smaller than the controlled, state-of-the-art hydroponic test results.

We respectfully request that the rule be remanded to the MPCA until it does a more complete cost analysis, and can demonstrate that the expenditure of billions of dollars will result in better protection of the use of wild rice for harvest by humans and wild life.

We respectfully suggest that MPCA has not met its obligations under the Administrative Procedures Act to demonstrate the need for and reasonableness of the proposed rule, specifically Proposed MN Rules 7050.0224 Subp. 5. A. (Line 7.17 – 7.12), and Proposed MN Rules 7050.0224 Subp. 5. B.1. (Line 7.25 – 8.17)

[151] Reference (15), per Minnesota Reviser RD4324A, Proposed Minn. R. 7050.0224, Subp.2

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Minnesota Numerical Sulfide Water Quality Standard Testimony

Prepared by: Douglas J. Fort, Ph.D.; President,

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Summary

1. Conflicts and ambiguities in the evidence presented by the MPCA;

The primary conflict discussed in the testimony provided is the lack of rationale in dismissing a hydroponic study conducted by Fort Environmental Laboratories and published in a well-respected peer-reviewed journal [2]. There is perceived bias in the studies used to determine the proposed sulfide standard in that the vast majority were either performed by MPCA or supported by MPCA.

2. How those conflicts and ambiguities have not been resolved by the MPCA in the SONAR;

To date these issues have been discussed briefly in the Final Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, MPCA, August 11, 2017). However, based on the testimony provided herein, the conflict with the interpretation and judgements made by MPCA will need further resolution.

3. Errors in material assumptions made or suppositions underlying such MPCA assumptions;

A discussion of potential errors made and the uncertainty surrounding the decisions made are discussed in the testimony presented. This includes other questions regarding data use and statistical analyses.

4. Identifying where the MPCA appears to have made policy judgements to support a proposed rule provision but provided no articulation of the policy judgments."

We provide discussion of judgements without clear support throughout the testimony.

5. Additional factual material for the record supporting a rational conclusion that is contrary to the MPCA's purported "rational basis:" for its rule revision.

We provide rationale supporting why Fort et al. (2017) [2] should be considered in the derivation of the standard and rule-revision process. Overall, it is unclear what is meant by "rationale basis"

Background

To address the practicability of this standard, a 21-day hydroponic study was previously performed initially [1] to determine the toxicity of sulfate to wild rice seeds and seedlings. The initial study indicated that sulfate does not adversely affect germination and early development of wild rice at concentrations below 5,000 mg/L over a 21-day hydroponic exposure. Some effects indicated at high sulfate concentrations were also observed in osmotically equivalent chloride treatments, and some sulfate-specific stimulatory effects may be attributable to the effects of sulfate as a plant nutrient. Sulfate in surface waters is reduced to sulfide by anaerobic bacteria in sediments, and sulfide is known to be much more toxic to aquatic organisms than sulfate. As an extension of the original hydroponics study [1] examining sulfate toxicity to developing wild rice, sulfide toxicity to early life-stage wild rice was evaluated under varying iron concentrations representative of those known to be present in sediment pore waters in Minnesota [2]. The sulfide toxicity threshold under varying iron concentrations was determined to facilitate a better understanding of the role of iron in altering sulfide toxicity.

Hydroponic Studies Evaluating Sulfide Toxicity (based on Fort et al. 2017 [2])

The primary objective of this study was to determine the toxicity of sulfide to wild rice seeds and seedlings collected from the State of Minnesota, USA. Preliminary studies were utilized to assign the most appropriate culture media and test conditions, identify sensitive test endpoints, establish a statistically-valid experimental design, and determine appropriate sulfide exposure concentrations for the range of selected wild rice response endpoints. Concentration-response data, including twenty-five percent inhibitory concentrations (IC25) values, and No and Lowest Observed Effect Concentrations (NOEC and LOEC) for the effects of sulfide on wild rice were determined.

Mesocotyl emergence was the most sensitive endpoint at sulfide concentrations ≥3.1 mg/L with 0.8 mg/L Fe and an IC25 value of 3.9 (3.5-4.3) mg/L sulfide. However, exposure of developing wild rice to sulfide concentrations ≥7.8 mg/L, IC25 values of 7.1 (6.5-7.7) and 9.3 (8.8-9.8) mg/L, was required to significantly reduce mesocotyl emergence with additions of 2.8 and 10.8 mg Fe/L, respectively. Moreover, addition of 10.8 mg/L Fe resulted in reduction of sulfide toxicity compared to lower iron concentration treatments, based on emergence, changes in median ET 30 values, and greater percent emergence in seeds exposed to 12.5 mg/L sulfide.

The least sensitive endpoints were seed activation, seedling survival, and phytotoxicity. Root and shoot growth endpoints were less sensitive than the emergence endpoints. The d 21 chronic values (ChV, geometric mean of NOEC and LOEC values) in the 0.8 mg Fe/L treatment set ranged from 2.2 mg/L sulfide for emergence to >12.5 mg/L sulfide for seed activation, survival, and phytotoxicity endpoints. The ChV values for replicates exposed to 2.8 and 10.8 mg Fe/L ranged from 4.9 mg/L sulfide for emergence to >12.5 mg/L sulfide for seed activation, survival, and phytotoxicity endpoints, providing evidence of a trend of decreased sulfide toxicity with increased iron concentration.

Historical studies of sulfide toxicity were reviewed by Lamers et al. [3]. Unfortunately, no studies with wild rice were included. However, studies with *Oryza sativa* (Asian rice) in hydroponic culture showed reduced productivity at 5 mg/L sulfide [4] and 0.9 mg/L sulfide [5], and radial oxygen loss and reduced at nutrient uptake at 0.3-1.9 mg/L sulfide [6]. More recently, Pastor et al. [7] demonstrated sulfide toxicity to wild rice at 0.3 mg/L sulfide which was markedly less than found in the present study. However, the effects measured were on juvenile seedling growth and development using seedlings which were produced from seeds allowed to germinate and grow to 1-2 cm (5-7 d) in aerobic deionized water, whereas Fort et al. [2] initiated exposure in un-germinated seeds under anaerobic conditions. Both studies utilized a modified Hoagland's solution [4,5], with the studies by Pastor et al. [12] containing 20% strength solution and 5 mM PIPES buffer and the present study using modified HS-1 solution contained 25% ammonium (molar basis) in a mixture of ammonium and nitrate. The hydroponics design [7] used total hypoxia to maintain sulfide levels, but exposed the vegetative portion of the rice plants to levels of sulfide which are much greater than would be expected in nature. The design of the hydroponics system used in the Fort et al. [2] study allowed the seed, mesocotyl and early primary leaf (shoot) to be exposed to the hypoxic media with sulfide which was supported by peer review of studies supporting the re-evaluation of the State of Minnesota's surface water quality standard for sulfate [8]. Test conditions that were more ecologically-realistic were recommended by peer-review [8] and thus, the basis for the design was a scaled-down model of ponds in which wild rice grow naturally. Overall, the primary fundamental differences between the laboratory hydroponics study and rice growing naturally were the lack of sediment in the simplified, but highly controlled hydroponics and omission of the floating leaf phase. In the case of the hydroponics design, allowing a floating leaf phase would have resulted in artificially greater exposure to sulfide due to the high levels of sulfide in the media which are not generally present at the surface of pond water. Oxidation of free sulfide in the water column resulting from greater oxygen levels naturally reduce free sulfide levels exposed to the floating leaves of wild rice.

Based on measured sulfide concentrations, iron substantially reduced free sulfide concentrations in the 10.8 mg Fe/L treatment relative to the 0.8 mg Fe/L treatment [2]. In general, the effect of 2.8 mg Fe/L on free sulfide concentrations fell between the 0.8 and 10.8 mg Fe/L treatments. These observations, combined with differences in wild rice responses to sulfide across different iron concentrations, showed the ability of iron to reduce sulfide toxicity to wild rice. Free sulfide loss between 24-h renewals ranged from 19.6 to 23.5% with 0.8 mg Fe/L, 32.4 to 55.6% with 2.8 mg Fe/L, and 87.6 to 95.4% with10.8 mg Fe/L, based on time-weighted average measurements which provide a more realistic estimation of exposure concentration. The loss was presumably due in part to degradation, but primarily complexation with iron. These results provide evidence that Fe reduces free sulfide concentrations, but not necessarily as a linear function of iron concentration [9-11]. Sulfide levels in pond sediment are determined by sulfate levels, availability, temperature, oxidative-reduction potential, pH, total organic carbon, Fe^{2+} levels, and speciation [10,11]. Sulfide phytotoxicity has been described historically by rotting roots, black (FeS plaque) root, discoloration of the leaves, and poor growth and yield since the late 1950s [12-14] resulting from sulfide-induced nutritional deficiencies resulting from poor uptake and utilization of critical nutrients [7, 12-17]. These deficiencies result in potential inhibition of various oxidases compromising metabolic capacity, inducing oxidative stress, and reducing gas exchange [18-22] in the root systems. Detoxification of sulfide by rice requires radial oxygen loss (ROL) from roots to the rhizosphere as described by Armstrong and Armstrong [18]. Armstrong and Armstrong [18] found that adventitious and fine lateral roots of rice exposed to sulfide had reduced ROL to the rhizosphere atomically characterized as being thickened resulting in inhibition of the apical cortical gas space system. More recent studies [23,24] have demonstrated mitochondrial-based detoxification of sulfide primarily in the roots. Functional isoforms of O-acetylserine(thiol)lyase C (OASTL), specifically OAS-C which detoxifies sulfide primarily in the roots [25] by catalyzing the conversion of sulfide and O-acetylserine to cysteine.

In Fort et al. (2017), black plaque was found on the seminal roots exposed to >7.8 mg/L sulfide and 2.8 or 10.8 mg/L Fe. However, blackening of the roots often observed in plants growing in sulfide laden sediment. Limited blackening of the roots was found in the present hydroponics study, however; we should not expect it as sediment co-factors such as organic carbon and a microbial flora are likely required to facilitate the process. Although it is plausible that OAS-C is responsible for detoxifying a portion of the sulfide exposed to the wild rice seedlings in the present study; based on the daily sulfide decay (ca. 30%), the wild rice seedling was still exposed to a significantly high level of free sulfide during the study. Thus, enzymatic sulfide detoxification in the roots cannot explain the decreased toxicity of sulfide observed in the present study even in the lower Fe treatment on a physiological level. Sulfide toxicity to wild rice also is tissue-dependent with the mesocotyl and roots being less susceptible to free sulfide toxicity and the photosynthetic portion being more susceptible to sulfide. On a larger scale, to properly evaluate sulfide toxicity to wild rice, both free sulfide and complexed sulfide need to be considered based the appearance of black plaque on the roots of wild rice seedlings from the higher sulfide and Fe treatments and the reduction of free sulfide toxicity by Fe found in the present study.

Results from this study indicated that exposure of developing wild rice (mesocotyl emergence) to sulfide induced toxicity ≥3.1 mg/L sulfide in the presence of 0.8 mg Fe/L, and ≥7.8 mg/L sulfide in the presence of 2.8 or 10.8 mg Fe/L at day 21. Mesocotyl emergence was the most sensitive endpoint, and growth endpoints were less sensitive. Increasing Fe concentrations reduced the toxic effects of sulfide to wild rice. Ultimately, determination of site-specific sulfate criteria that consider factors that alter toxicity, including sediment Fe and organic carbon, are necessary to adequately address the potential impact of sulfate in surface waters. Additional study of the larger significance of the hydroponics study considering aquatic lifecycle evaluation of sediment sulfide toxicity to wild rice using a sediment microcosm is warranted.

Proposed Sulfide Standard

MPCA is proposing a protective level of 120 μg/L sulfide in the new water quality standard.

Issues with the Proposed Sulfide Standard

Issues with the proposed standard can be summarized in two areas:

1. Refutation of Sulfide Toxicity and Sulfide Detoxification from Fort et al. (2017), and
2. Basis for and Approach to the Proposed Standard
3. Continued Refutation of Sulfide Toxicity and Sulfide Detoxification from Fort et al. (2017) – Additional Study

Refutation of Interpretation of Sulfide Toxicity and Sulfide Detoxification from Fort et al. (2017)

"A 21-day hydroponic study was sponsored by the Minnesota Chamber of Commerce (Fort Environmental Laboratory, 2015; Fort et al., 2017) in which wild rice seeds from a Minnesota lake were germinated in solution with a range of sulfide concentrations. Fort et al. (2017) did not calculate effect concentrations, but an EC10 of 963 µg/L was calculated from the Fort study data (MCC, 2015), suggesting that sulfide is less toxic to wild rice than was found in the three MPCA-sponsored studies (hydroponic, outdoor mesocosm, and field survey).

MPCA staff reviewed the design and results of the Fort hydroponic experiments to explore whether there were differences in the experimental approaches that could help account for these differing results. One potential explanation for the difference in the observed toxicity effects lies in the way that the germinated seeds were exposed to sulfide. In the Fort study, seeds were placed on a mesh that was submerged 1 cm in an aquarium open to the atmosphere that initially contained an anaerobic hydroponic solution of a given sulfide concentration; the solution was renewed and monitored daily. During the 21-day experiment, the sprouts were enabled to grow above the surface of the water, into the room air, as the mesocotyl (stem) developed and elongated. As the Fort study report states, "The mesocotyl developed in aerobic conditions under this design. Plastic wire mesh was placed inside the aquaria to provide a trellis to support vegetative growth above the hypoxic culture media." (Fort Environmental Laboratory, 2015, p. 14).

MPCA staff hypothesize that once the wild rice sprouts emerged into the room air, access to oxygen in the room air allowed the sprouts to internally detoxify sulfide by oxidizing it to non-toxic forms of sulfur (see How access to oxygen may allow wild rice to detoxify sulfide, in Part A of this chapter). There is evidence in the scientific literature that aquatic plants can detoxify sulfide through two broad routes that require oxygen. Aquatic plants have special channels in the stem for transporting air, called aerenchyma, for this purpose (Colmer, 2003). Access to the atmosphere is significant because the atmosphere is 21% oxygen (210,000 parts per million, ppm), in contrast to the availability of oxygen in water (a maximum of about 10 ppm). However, as noted in Part A of this chapter, under natural conditions 21-day old wild rice plants would not have access to the atmosphere because the seeds germinate in water that is much deeper than 1 cm, and the stems would not yet have elongated sufficiently to reach the water surface." (Excerpted from: **Final Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, MPCA, August 11, 2017, p. 37-38).**

Regarding the study described above (Fort et al., 2016), MPCA stated, "*Access to the atmosphere is significant because the atmosphere is 21% oxygen (210,000 parts per million, ppm), in contrast to the availability of oxygen in water (a maximum of about 10 ppm). However, as noted in Part A of this chapter, under natural conditions 21-day old wild rice plants would not have access to the atmosphere because the seeds germinate in water that is much deeper than 1 cm, and the stems would not yet have elongated sufficiently to reach the water surface."* Conversion of H_2S to either SO_4^{2-} or elemental sulfur (S^0) is described in the equations below.

Depending on the reaction 1-2 moles of O_2 is required to convert 1 mole of H_2S to elemental S or sulfate, respectively. Thus, we acknowledge that excess oxygen relative to sulfide is required in water for conversion to sulfate or SO_4^{2-} or S^0, and that is substantially more O_2 in air than in water. Therefore, based on the DO levels present in the hydroponics system, a proportion of the H_2S could have converted to S^0 or SO_4^{2-}. Regardless of how much O_2 is present, only a certain fraction can be effectively by plant. Thus, the difference between atmospheric O_2 and water as the source is not as important as whether the concentration was adequate to facilitate detoxification. However, more significantly at the pH in hydroponic studies ranged from 7.0-7.5 at a significant proportion of the sulfide would have existed as HS- and considering the addition of Fe to the system, FeS. The sulfide loss over 24 hours in the hydroponic system was about 20-24%, 32-56%, and 88-94% with the addition of 0.8, 2.8, and 10.8 mg/L Fe indicating that reduced sulfide toxicity in the hydroponics was more likely due to loss from the system and conversion to FeS which is less overtly toxic to wild rice than sulfide. Since loss of free sulfide increases with increasing Fe addition, we suspect that a significantly proportion of the sulfide was converted to FeS. Therefore, MPCA's statement is based only on the assumption that only detoxification by the rice plant itself resulted in lower toxicity of sulfide, whereas it is the physicochemistry of the hydroponic environment also resulted in chemical reduction in free sulfide due to conversion to FeS which is misleading.

- $H_2S + 2O_2 \longleftrightarrow SO_4^{2-} + 2H^+$
- $2H_2S + O_2 \rightarrow 2H_2O + 2S^0$
- $Fe^{2+} + H_2S \rightarrow FeS + 2H^+$

Both the sulfate hydroponic (Fort et al. 2014) and sulfide hydroponic (Fort et al. 2017) were highly-control GLP-compliant laboratory studies that were highly scrutinized during their conduct and publication process through peer-review. Thus, the present study should be considered in the evaluation of criteria selection and is important in evaluating other factors in the environment that modulate and often mitigate sulfide toxicity to wild rice.

Basis for and Approach to the Proposed Standard

Statement of Primary Factors

"B. That other factors affect wild rice does not negate the need to protect wild rice from excess sulfide

Multiple stressors affect wild rice in nature.

"Some comments received in regards to the March 2015 Draft Proposal (MPCA, 2015) focused on regulating sulfate. Others suggested that a) it is inappropriate to regulate sulfate without also addressing the many other factors, aside from sulfide, that likely control the presence of wild rice, and b) factors other than sulfate (and sulfide) are more important in controlling the suitability of wild rice habitat. It was further suggested that it is not appropriate to use field data to identify a sulfide concentration that is protective of wild rice both because field data are inherently variable and in light of the multiple stressors that were not studied in the MPCA-sponsored research, especially a) changes in water levels from year to year, b) impacts of development, and c) presence of invasive or competitive species.

It is true that there is more "noise" in field data than in a controlled experiment. Because of this noise, or data variability, it is more challenging to detect a statistically significant impact of a particular stressor in field data; there is more statistical power in controlled laboratory experiments (Chapman, 2002). It is important to conduct controlled laboratory experiments to determine that a particular stressor (such as sulfide) has the potential to negatively affect a species, but the ecological significance of that effect is ambiguous until mesocosm or field data are collected (Chapman, 2002). If, despite environmental variability, a statistically significant relationship is demonstrated in the field that reinforces the laboratory finding, then there is little question that the chemical is important in controlling the occurrence of that species in the environment.

Despite the challenge of documenting a statistically significant relationship in field data, the binary logistic regression (BLR) analysis found a statistically significant negative correlation between the concentration of sulfide in the sediment porewater and the occurrence of wild rice (p=0.001, Table 1-5). Performing multiple BLR with more than one variable demonstrated that porewater sulfide is one of three primary independent variables correlated with wild rice occurrence (Myrbo et al., in press-1): porewater sulfide, water transparency, and water temperature. The statistical analysis strongly supports the conclusion that sulfide independently affects wild rice presence and absence (p=0.001; Table 1-3), which implies that limiting sulfate availability has the potential to protect wild rice from elevated sulfide. Analysis of the MPCA field data shows that porewater sulfide is simultaneously controlled by surface water sulfate and sediment concentrations of total organic carbon (TOC) and total extractable iron (TEFe) (Pollman et al., in press; discussed in Part D of this chapter). Interestingly, sulfate, TOC, and TEFe do not have any statistically significant effect on wild rice occurrence when considered individually (p= 0.15, 0.79, and 0.48, respectively; Table 1-3; Myrbo et al., in press-1). These three environmental variables only have a relationship to the occurrence of wild rice when they are considered simultaneously, given that particular combinations of the three can produce excessive concentrations of porewater sulfide (Part E of this Chapter).

Factors that act independently of porewater sulfide may also affect wild rice growth, such as hydrological changes and exotic species (Tables 1-6 and 1-7), but unless a factor has an effect on the relationship between sulfate and sulfide, consideration of such a factor is irrelevant to the mission of protecting wild rice from excess sulfide. The only factors that have been identified that have an effect on porewater sulfide are sulfate, sediment TOC, and sediment iron (Pollman et al., in press). However, one exception may be sites with upwelling groundwater; it has been reported that such sites may be favorable habitat for wild rice (Table 1-6). Consistent upward groundwater flow would break the usual relationship between sulfate in surface water and sulfide in porewater, because sulfate would be less likely to move downwards into the sediment when groundwater is moving upwards. Therefore, at some sites the sulfate concentration of the groundwater may be more important than the surface water in controlling the production of porewater sulfide, but statistical analysis shows that at most sites porewater sulfide is a function of surface water sulfate (Pollman et al., in press). Even if this were not the case, the possibility that groundwater, rather than surface water, controls porewater sulfide in a specific wild rice bed does not negate the validity of the empirically observed, statistically significant, relationship between surface water sulfate, sediment iron, sediment TOC, and porewater sulfide as a general matter (Part D of this chapter, below; Pollman et al., in press)." (Excerpted from: **Final**

Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, MPCA, August 11, 2017, p. 23-24).

"The production of sulfide, while negative for wild rice growth at higher porewater concentrations, also affects other variables, causing other observed correlations with wild rice (Tables 1-2, 1-3, and 1-4). These sulfide-related correlations with wild rice can be either negative, such as between wild rice and porewater potassium (K), or positive, such as the positive correlation of wild rice with porewater iron. <u>The latter is the easiest to understand, because dissolved sulfide and dissolved iron react with each other to form a solid precipitate of iron sulfide. When porewater iron is high, sulfide is low, resulting in a positive correlation between porewater iron and wild rice, which is weaker ($p < 0.01$) than the negative correlation between porewater sulfide and wild rice ($p < 0.001$).</u> (Excerpted from: **Final Technical Support Document: Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice, MPCA, August 11, 2017, p. 11)."**

Although it is not difficult to understand the negative correlation between pore water sulfide and the presence of wild rice using BLR, and that porewater sulfide water transparency, and water temperature also correlated with rice occurrence; it is not clear why the following is justified.

<u>"The statistical analysis strongly supports the conclusion that sulfide independently affects wild rice presence and absence (p=0.001; Table 1-3), which implies that limiting sulfate availability has the potential to protect wild rice from elevated sulfide."</u>

The suggestion that sulfide acts independently to affect the presence and absence of wild rice implies there is no interaction between sulfide or any other variable that could potentially influence sulfide presence and bioavailability which is not justified based on historical understanding of sediment sulfide and interactions with other factors described below. I found no attempt to evaluate interactions within the logistic regression. Although this complicates the analyses, it does provide ecological credence in that the ecosystem is not a binary function, it operates in an interactive manner with at least several of the variables considered potentially interacting with each other. Not to at least consider interaction elements in the model, is an over-simplification of the system.

<u>"Interestingly, sulfate, TOC, and TEFe do not have any statistically significant effect on wild rice occurrence when considered individually (p= 0.15, 0.79, and 0.48, respectively; Table 1-3; Myrbo et al., in press-1). These three environmental variables only have a relationship to the occurrence of wild rice when they are considered simultaneously, given that particular combinations of the three can produce excessive concentrations of porewater sulfide (Part E of this Chapter)."</u>

The thought that sulfate, TOC, or Fe didn't have a direct impact on the presence or absence of wild rice is not surprising, as is the thought that their significance in terms of affecting the presence or absence of wild rice is simultaneous. Each of these variables interact directly or indirectly with sulfide to module toxicity. Thus, these statements oversimplify a complicated system in which the toxicity of sulfide which is not in question is modulated by other factors including sulfate, and to a greater extent, TOC and Fe begging the question, why was multiple linear regression not used in the analysis of this data?

"When porewater iron is high, sulfide is low, resulting in a positive correlation between porewater iron and wild rice, which is weaker ($p < 0.01$) than the negative correlation between porewater sulfide and wild rice ($p < 0.001$)."

Comparison of the degree of correlation using statistical significance porewater Fe and the presence of wild rice and negative correction between sulfide and the presence or absence of wild rice to support the importance of one variable over the other cannot be supported empirically or statistically without consideration of interaction. The importance of Fe cannot be discounted and should be as a significantly variable. Further, evaluating the interactions of each of the variables simultaneously would support an interactive effect between them, thus reducing an over-reliance on binary comparison. The point is, comparison of any means of sulfide toxicity in the environment without consideration of the other confounding variables, Fe and TOC is not justified without further statistical analyses.

Continued Refutation of Sulfide Toxicity and Sulfide Detoxification from Fort et al. (2017) – Additional Study

FEL was retained by the Iron Mining Association of Minnesota (IMAM) to conduct a study of sulfide toxicity to wild rice (*Zizania palustris*) using a partially hypoxic hydroponic exposure. The sulfide toxicity threshold was determined to facilitate a better understanding of the role of iron in altering sulfide toxicity, and will be used to support the efforts to re-evaluate the State of Minnesota's sulfate water quality standard of 10 mg/L for wild rice. The primary objective of the study IMAM01-00420 was to determine if the depth of hydroponic exposure affected the toxicity of sulfide to wild rice (*Zizania palustris*) seed from the State of Minnesota, USA by comparing the results of the present study to the original hydroponics study of sulfide toxicity, Fort et al. (2). Concentration-response data, including No and Lowest Observed Effect Concentrations (NOEC and LOEC), chronic values (ChV), and 25% inhibitory concentrations for the effects of sulfide on wild rice were determined.

The definitive wild rice sulfide toxicity study was conducted in a static-renewal format as prescribed by Fort et al. (1) and study ENVI01-00352 in an environmental chamber equipped for hydroponic studies (Table 3). Test solution (0.7 of total volume) was renewed daily. Each of the four replicates per solution contained two 1 L mesh-lined sub-baskets. The inert plastic mesh served as the medium on which the seeds were placed and served as a physical support required for hydroponic culture. Each basket contained 80 seeds (320 total per exposure condition), which was adequate to evaluate concentration-response relationships and assess significant differences in the treatments relative to their respective control (i.e., the HS-1 medium with a given iron concentration and no sulfide) (3,4). The study was performed in the dark to promote mesocotyl emergence and development.

Water temperature was maintained at $21^{\circ} \pm 2^{\circ}C$ (day) and $12 \pm 2^{\circ}C$ (night). Test solution pH was maintained between 6 and 7.5 s.u. in the control and treatment exposures. Within a given replicate, variation in pH was ±0.5 s.u. for each daily measurement at T0 and T24, and over the course of the study. This pH range was well within the range of conditions present where wild rice grows naturally. This range is also well within the range where the dynamic equilibrium between H_2S and HS^- shifts dramatically (~7.0), and these sulfur species are thought to differ in their toxicity. In order to maintain hypoxic (DO <2.0 mg/L) conditions within the hydroponic tanks, the HS-1 test medium was deoxygenated with N_2 gas, stored in a sealed carboy until used, and checked for oxygen concentration immediately prior to use. Each hydroponic tank was equipped with a 6-inch, small-bubble air stone to deliver a constant flow of N_2 gas to the tank and ensure hypoxic conditions were maintained. For hypoxic root growth and aerobic vegetative growth, the basket was placed in the hydroponic aquaria such that the seeds resided in the culture media approximately 6 cm below the air:media interface in contrast to the Fort et al. (2) study in which the seed depth below the water surface was 1 cm.. The mesocotyl developed in aerobic conditions under this design. Plastic wire mesh was placed inside the aquaria to provide a trellis to support vegetative growth above the hypoxic culture media. Sulfide-treated test solutions were prepared daily for use in renewal. Sulfide concentrations in the test solutions were measured prior to and following each daily media renewal using an ion-selective probe. The stability of sulfide in the culture media was aided by the N_2 gas balance in the media.

Visual assessments only (i.e., no plants harvested) of the following endpoints (Table 4) were conducted at SD 10 following dark-phase exposure to evaluate:

- Activation expressed as % activation;
- Mesocotyl Emergence expressed as % emergence;
- Time to emergence expressed as the time to 30% emergence (ET30) at the replicate and treatment levels;
- Seedling survival expressed as % survival; and
- Phytotoxicity expressed as % affected.

Results (see table below) from this study indicate that for the most sensitive endpoint (mesocotyl emergence), exposure of developing wild rice to sulfide at concentrations ≥3.12 mg/L sulfide was toxic based on assessment of NOEC and LOEC values in the presence of 0.8 mg/L Fe. However, exposure of developing wild rice to sulfide at concentrations ≥7.8 mg/L was necessary to significantly reduce emergence in the presence of 2.8 mg Fe/L. Mesocotyl emergence was the most sensitive endpoint in the study, while seed activation, seedling survival, and phytotoxicity were the least sensitive endpoints. Based on measured sulfide concentrations, Fe reduced free sulfide concentrations in the 2.8 mg Fe/L treatment relative to the 0.8 mg Fe/L treatment. These observations, combined with differences in wild rice responses to sulfide across the different iron concentrations, demonstrate the ability of Fe to reduce sulfide toxicity to wild rice.

Endpoint	Study Day 10 NOEC/LOEC (mg/L S^{2-})		ChV (mg/L S^{2-})[1]	IC25 (mg/L S^{2-})[2]
	0.8 mg Fe/L	2.8 mg Fe/L	0.8/2.8 mg Fe/L	0.8/2.8 mg Fe/L
Activation	7.78/>7.78 [12.5/>12.5][3]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78/>7.8 [>12.5]/ [>12.5]
Emergence (%)	1.56/3.12 [3.12/7.78]	3.12/7.78 [3.12/7.78]	2.34/5.45 [4.9/4.9]	2.09 (1.94-2.24)/2.68 (2.42-2.94) [3.5 (3.1–3.9)]/[5.7 (5.3-6.1)]
Emergence (ET30)[4]	7.78/>7.78 [3.12/7.78]	7.78/>7.78 [3.12/7.78]	>7.78/>7.78 [3.12/7.78]	---/--- [---/---]
Survival	7.78/>7.78 [12.5/>12.5]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]
Phytotoxicity	7.78/>7.78 [12.5/>12.5]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]

As observed in Fort et al. (2), the addition of 2.8 mg/L Fe reduced the toxicity (emergence) of sulfide indicating that the depth of hydroponic exposure during mesocotyl emergence and early growth was not a significant factor in the sensitivity of wild rice to sulfide. In the present study, a greater effect of Fe in reducing the effects of sulfide on mesocotyl emergence was noted at SD 10 compared to Fort et al. (2) based on NOEC and LOEC values, but the IC25 values were comparable. Results from these studies demonstrated that adequate oxygen was most likely not present at sufficient levels in the test media to support detoxification based on the hypoxic environment, complexation with Fe is the primary mitigating factor in terms of sulfide toxicity. Thus, the results suggest that detoxification of sulfide in the Fort et al. (1) were also the result of Fe complexation rather than detoxification by the plant itself.

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[1] Chronic Value = geometric mean of NOEC and LOEC values.
[2] 25% inhibitory concentration determined by linear interpolation.
[3] Values from Fort et al. (1) in [ ].
[4] Time to 30% emergence. Significance based on Mann-Whitney U test, $p<0.05$.

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TEST ITEM

Sulfide

STUDY TITLE

Hydroponics-Based Sulfide Toxicity Testing of Wild Rice (*Zizania palustris*) – Depth Evaluation

DATA REQUIREMENT

Definitive Phase

STUDY DIRECTOR AND AUTHOR

Douglas J. Fort, Ph.D.

STUDY COMPLETION DATE

November 21, 2017

PERFORMING LABORATORY

Fort Environmental Laboratories, Inc.
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Stillwater, OK 74074

REPORT NUMBER

IMAM01-00420

Total Pages: 88

CERTIFICATION

The undersigned, declare that this report provides an accurate evaluation of the data obtained from this study.

Study Director:

	11/20/2017
Douglas J. Fort, Ph.D., Study Director, FEL	Date

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LIST OF ACRONYMS

ANOVA – analysis of variance
B – boron
ChV - Chronic value (geometric mean of NOEC and LOEC value)
DO – dissolved oxygen
dw – dry weight
EC – effective concentration
FEL – Fort Environmental Laboratories
IC – inhibitory concentration
KW ANOVA – ANOVA on ranks
L - liter
LC – lethal concentration
LOEC –lowest observed effects concentration
ET30 – time to 30% emergence
NOEC – no observed effects concentration
ORP – oxidation/reduction potential
PAH – polyaromatic hydrocarbon
SEM – standard error of the mean
SOP – standard operating procedure
SD – Study Day

1. SUMMARY

Guidelines:	Protocol IMAM01-00420
Study Initiation Date:	November 3, 2017
Experimental Start / End Dates:	November 3, 2017 / November 13,2017
Test Treatments:	1) Sulfide Treatments - HS-1 (1:4 ammonia-N:nitrate-N) [control], 0.3, 1.56, 3.12, 7.78 mg/L sulfide in the presence of 0.8 or 2.8 mg/L Fe.
Time-Weighted Average (TWA) Test Concentrations (fresh solutions at renewal):	1) Sulfide Treatments - HS-1 (1:4 ammonia-N:nitrate-N) [control] <0.01, 0.43, 1.64, 3.20, and 7.71 mg/L sulfide each with 0.8 mg/L Fe; and 2) HS-1 (1:4 ammonia-N:nitrate-N) [control] <0.01, 0.37, 1.64, 3.31, and 7.53 mg/L sulfide each with 2.8 mg/L Fe.
Age of Test Subject:	Seed
Source of Seeds:	Minnesota, USA
Summary of Endpoints	See Table 1

1.1. METHOD

The definitive wild rice sulfide toxicity study was conducted in a static-renewal format in an environmental chamber equipped for hydroponic studies (Table 3) as prescribed by Fort et al. (1) and study ENVIO1-00352. Test solution (0.7 of total volume) was renewed daily. Each of the four replicates per solution contained two 1-L mesh-lined sub-baskets. Plastic mesh served as the medium on which the seeds were placed and served as physical support required for plants growing in hydroponic culture. Each sub-basket contained 40 seeds (80/replicate at T0, total seed number = 320 per treatment), which was adequate to evaluate concentration-response relationships and assess significant differences in the treatments relative to the control. The 10 study days (SD) were performed in the dark to promote mesocotyl emergence and development simulating sediment.

Visual assessments only (i.e., no plants harvested) of the following endpoints were conducted at SD 10 following dark-phase exposure to evaluate:

- Activation expressed as % activation;
- Mesocotyl Emergence expressed as % emergence;

- Time to emergence expressed as the time to 30% emergence (ET30) at the replicate and treatment levels;
- Seedling survival expressed as % survival; and
- Phytoxicity expressed as % affected.

1.2. RESULTS AND CONCLUSIONS

Results from the IMAM01-00420 study met the performance criteria established from Fort et al. (2017). Therefore, results from the study are considered valid. A summary of the 00420 results is provided in Table 1. A consistent and anticipated adverse response to 100 mg B/L exposure was noted. The pH was maintained at 6.0 to 7.5 s.u. in all replicates of the control and sulfide treatments, and ±0.5 s.u. within a given replicate for each daily measurement at T0 and T24 over the course of the study. DO levels were maintained at <2.0 mg/L in all treatments during the course of the study. Hydroponic chamber temperature was maintained at 21º ± 2ºC (day) and 12 ± 2ºC (night) in all replicates of control and treatments. The inter-replicate CV for both pre- and post-renewal TWA sulfide concentrations was ≤20% for each HS-1 control and associated sulfide treatments, indicating low variability between replicates of a given treatment or control. Free sulfide loss between 24-hour renewals ranged from 22.3 to 29.7% in the 0.8 mg Fe/L treatments, and 40.2% to 58.6% in the 2.8 mg Fe/L treatments, respectively based on TWA measurements. The loss was presumably due in part to degradation, but primarily complexation with Fe. These results demonstrate that iron reduces free sulfide concentrations, but not necessarily as a linear function of iron concentration.

Key findings from study 00420, expressed as nominal sulfide concentrations, included:

- Decreased emergence and increased median ET30, and the occurrence of phytotoxicity were observed in wild rice exposed to 100 mg B/L relative to the HS-1 control with 0.8 mg Fe/L.
- Sulfide exposure did not affect seed activation, seedling survival, or induce phytotoxicity at 7.78 mg/L in either of the Fe treatments.
- Emergence was the most sensitive endpoint, with respective SD 10 NOEC and LOEC values of 1.56 mg/L and 3.12 mg/L sulfide for the 0.8 mg/L Fe treatment; and 3.12 and 7.78 mg Fe/L for the 2.8 mg/L Fe treatment.
- As observed in Fort et al. (1), the addition of 2.8 mg/L Fe reduced the toxicity (emergence) of sulfide indicating that the depth of hydroponic exposure during mesocotyl emergence and early growth was not a significant factor in the sensitivity of wild rice to sulfide. In the present study, a greater effect of Fe in reducing the effects of sulfide on mesocotyl emergence was noted at SD 10 compared to Fort et al. (1) based on NOEC and LOEC values, but the IC25 values were comparable.
- Results from these studies demonstrated that adequate oxygen was most likely not present at sufficient levels in the test media to support detoxification based on the hypoxic environment, complexation with Fe is the primary mitigating factor in terms of sulfide toxicity. Thus, the results suggest that detoxification of sulfide in the Fort et al. (1) were also the result of Fe complexation rather than detoxification by the plant itself.

Table 1. Summary of Measurement Endpoints at SD 10[1]

Endpoint	Study Day 10 NOEC/LOEC (mg/L S^{2-})		ChV (mg/L S^{2-})[2]	IC25 (mg/L S^{2-})[3]
	0.8 mg Fe/L	2.8 mg Fe/L	0.8/2.8 mg Fe/L	0.8/2.8 mg Fe/L
Activation	7.78/>7.78 [12.5/>12.5][4]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78/>7.8 [>12.5]/ [>12.5]
Emergence (%)	1.56/3.12 [3.12/7.78]	3.12/7.78 [3.12/7.78]	2.34/5.45 [4.9/4.9]	2.09 (1.94-2.24)/2.68 (2.42-2.94) [3.5 (3.1–3.9)]/[5.7 (5.3-6.1)]
Emergence (ET30)[5]	7.78/>7.78 [3.12/7.78]	7.78/>7.78 [3.12/7.78]	>7.78/>7.78 [3.12/7.78]	---/--- [---/---]
Survival	7.78/>7.78 [12.5/>12.5]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]
Phytotoxicity	7.78/>7.78 [12.5/>12.5]	7.78/>7.78 [12.5/>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]	>7.78 [>12.5]/ >7.78 [>12.5]

2. INTRODUCTION

FEL was retained by the Iron Mining Association of Minnesota (IMAM) to conduct a study of sulfide toxicity to wild rice (*Zizania palustris*) using a partially hypoxic hydroponic exposure. An assessment of the ability of iron to reduce sulfide toxicity to wild rice was also performed. The study will ultimately be used to assist in understanding the role of water-column based sulfate in the toxicity of sediment porewater sulfide to wild rice. The sulfide toxicity threshold was determined to facilitate a better understanding of the role of iron in altering sulfide toxicity, and will be used to support the efforts to re-evaluate the State of Minnesota's sulfate water quality standard of 10 mg/L for wild rice. The study was conducted in accordance with the specifications identified in FEL's Quality Assurance Management Plan (QAMP) (2), relevant facility standard operating procedures (SOPs), and Study Protocol No. IMAM01-1 prepared for FEL Study No. IMAM01-00420.

The primary objective of the study IMAM01-00420 was to determine if the depth of hydroponic exposure affected the toxicity of sulfide to wild rice (*Zizania palustris*) seed from the State of Minnesota, USA by comparing the results of the present study to the original hydroponics study of sulfide toxicity, Fort et al. (1). Concentration-response data, including No and Lowest Observed Effect Concentrations (NOEC and LOEC), chronic values (ChV), and 25% inhibitory concentrations for the effects of sulfide on wild rice were determined.

3. STUDY PERSONNEL

- Dr. Kurt Anderson, Minnesota Power – Sponsor Representative
- Dr. Douglas J. Fort, FEL – Study Director

[1] Nominal concentrations. Significance based on ANOVA or KW-ANOVA, $p \leq 0.05$.
[2] Chronic Value = geometric mean of NOEC and LOEC values.
[3] 25% inhibitory concentration determined by linear interpolation.
[4] Values from Fort et al. (1) in [ ].
[5] Time to 30% emergence. Significance based on Mann-Whitney U test, $p<0.05$.

- Ms. Deanne Fort, FEL – Manager, In-life study facility

4. MATERIALS AND METHODS

4.1. DILUTION WATER

FEL used deionized water as the base water for this study. The deionized laboratory water was prepared by passing tap water through a four-filter system: a multimedia filter to remove suspended solids in the feed water; a 10 inch pre-treatment filter (5 µm) to remove any additional solids; a 3.6 ft^3 activated virgin carbon treatment filter to remove chlorine, ammonia, and higher molecular weight organics; 1.2 ft^3 cation, 1.2 ft^3 anion, and two 1.2 ft^3 mixed bed ion exchange polishing filters in series to deionize the water. Both polishing filters were equipped with conductivity detection systems. Water exceeding 5 µmhos/cm was signaled by a warning light. A 5 µm solid filter completed the water treatment process and ensures no solids are released during deionization. Seven water quality characteristics of the laboratory water were monitored twice per month: pH, dissolved oxygen (DO), conductivity, hardness, alkalinity, ammonia, and residual oxidants. Additional water quality characteristics measured at least annually were iodide, polyaromatic hydrocarbons (PAHs), pesticides, and metals. The dilution water was most recently analyzed for pesticides, PAHs, and metals in February 2017, and all water quality measurements cited above met the U.S. EPA and American Society for Testing and Materials (ASTM) criteria for aquatic toxicity test culture water. Deionized water was used to prepare the culture media in accordance with Tables 2-5. Basic water chemistry parameters such as pH, hardness, and conductivity were documented on a representative sample of each test medium evaluated.

4.2. TEST SUBSTANCE

Hydrated sodium sulfide ($Na_2S \cdot 9\ H_2O$, 99.99% pure, SigmaAldrich, St. Louis, MO, lot number MKBP2953V, expiration 7/2021) and ferric chloride ($FeCl_3$, 98.00%, Merck KGaA, lot number 018400, expiration 11/2015) were used throughout the study.

4.3. TEST SYSTEM

The test system was wild rice (*Zizania palustris*). Given that wild rice seeds were obtained from natural stands in Minnesota, care was taken to ensure that damaged or deformed seeds were not selected for the experiment. Seeds were sieved through a #5 (4 mm) sieve followed by a #10 (2 mm) sieve to separate quality seeds from debris. Visual inspection was also conducted as seeds were loaded into test systems to ensure damaged, discolored, or deformed seeds were not utilized.

4.3.1. ORIGIN AND HANDLING

Wild rice was hand-harvested from Minnesota. The ziplock bag containing wild rice seed was sent to FEL on November 2, 2017 by Kurt Anderson and received by FEL on November 3, 2017. Upon receipt the wild rice seed was unpacked, and stored at 4°C in the dark.

4.4. EXPOSURE SYSTEM

Test solutions were provided using a static-renewal design in 10 L hydroponic tanks. The renewal frequency was daily with 0.7 volume exchanges/day. Daily cleaning of the tanks using a turkey baster was performed during media renewal to remove biomass that may have grown during the course of the study. This helped minimize bio-fouling and maintained water quality, including ammonia accumulation, in the tanks. Care was taken not to disturb the seeds and seedlings.

The hydroponic tanks were plastic aquaria (approximate measurements of 35 x 20 x 15 cm deep) equipped with baskets with inert mesh to support the seeds and seedlings. Each of the four tanks per treatment contained two 1-L baskets to house seeds and seedlings evaluated on study day (SD) 10. In total, eight baskets within the four replicates of wild rice seeds were evaluated per treatment and control.

Water temperature was maintained at 21º ± 2ºC (day) and 12 ± 2ºC (night). Test solution pH was maintained between 6 and 7.5 s.u. in the control and treatment exposures. Within a given replicate, variation in pH was ±0.5 s.u. for each daily measurement at T0 and T24, and over the course of the study. This pH range was well within the range of conditions present where wild rice grows naturally. This range is also well within the range where the dynamic equilibrium between H_2S and HS^- shifts dramatically (~7.0), and these sulfur species are thought to differ in their toxicity. In order to maintain hypoxic (DO <2.0 mg/L) conditions within the hydroponic tanks, the HS-1 test medium was deoxygenated with N_2 gas, stored in a sealed carboy until used, and checked for oxygen concentration immediately prior to use. Each hydroponic tank was equipped with a 6-inch, small-bubble air stone to deliver a constant flow of N_2 gas to the tank and ensure hypoxic conditions were maintained. For hypoxic root growth and aerobic vegetative growth, the basket was placed in the hydroponic aquaria such that the seeds resided in the culture media approximately 6 cm below the air:media interface in contrast to the Fort et al. (1) study in which the seed depth below the water surface was 1 cm.. The mesocotyl developed in aerobic conditions under this design. Plastic wire mesh was placed inside the aquaria to provide a trellis to support vegetative growth above the hypoxic culture media. Sulfide-treated test solutions were prepared daily for use in renewal. Sulfide concentrations in the test solutions were measured prior to and following each daily media renewal using an ion-selective probe. The stability of sulfide in the culture media was aided by the N_2 gas balance in the media. A summary of the study conditions is provided in Table 2.

4.4.1. EXPOSURE SYSTEM MAINTENANCE

Exposure tanks were siphoned on a daily basis to remove waste and any accumulated debris. Care was taken to minimize stress and trauma to the seeds/seedlings, especially during movement, cleaning of aquaria, and manipulation. Potentially stressful conditions and rapid changes in environmental conditions (light availability, temperature, pH, DO) were avoided.

4.5. WATER QUALITY ANALYSES

4.5.1. WATER (CULTURE) QUALITY ANALYSES

In each replicate tank, temperature and light intensity (lux) were measured daily throughout the 10-d study. DO (aqueous and headspace), pH, oxidation/reduction potential (ORP), and sulfide were measured twice daily (i.e., prior to and following solution renewal). DO, ORP, and sulfide measurements were conducted at the same water depth as seed exposure. Additionally, specific conductance (conductivity), total hardness, total alkalinity, total Fe, total residual oxidants, ammonia-nitrogen, sulfate, nitrate, and phosphate were measured in the media in a replicate of each treatment at SD 0, 7, and 10 (conclusion) of the in-life phase.

4.6. TEST METHOD

The definitive wild rice sulfide toxicity study was conducted in a static-renewal format as prescribed by Fort et al. (1) and study ENVI01-00352 in an environmental chamber equipped for hydroponic studies (Table 3). Test solution (0.7 of total volume) was renewed daily. Each of the four replicates per solution contained two 1 L mesh-lined sub-baskets. The inert plastic mesh served as the medium on which the seeds were placed and served as a physical support required for hydroponic culture. Each basket contained 80 seeds (320 total per exposure condition), which was adequate to evaluate concentration-response relationships and assess significant differences in the treatments relative to their respective control (i.e., the HS-1 medium with a given iron concentration and no sulfide) (3,4). The study was performed in the dark to promote mesocotyl emergence and development.

Visual assessments only (i.e., no plants harvested) of the following endpoints (Table 4) were conducted at SD 10 following dark-phase exposure to evaluate:

- Activation expressed as % activation;
- Mesocotyl Emergence expressed as % emergence;
- Time to emergence expressed as the time to 30% emergence (ET30) at the replicate and treatment levels;
- Seedling survival expressed as % survival; and
- Phytotoxicity expressed as % affected.

4.7. BIOLOGICAL ENDPOINTS / OBSERVATIONS

4.7.1. DATA COLLECTION AND BIOLOGICAL ENDPOINTS

Test data and daily observations were recorded in the study records. Study records included study tracking sheets, test information sheets, study calendars identifying major events, study logs for recording detailed observations and comments, activation, daily mesocotyl emergence, seedling survival, and test termination data sheets. Endpoints selected for the present study were based on those required by OECD Test No. 208 (5). The endpoints assessed were activation, mesocotyl emergence, and seedling survival (all of which were measured daily), and signs of phytotoxicity (wilting, chlorosis, stem and root rot). Table 3 provides an overview of the endpoints and the corresponding observation time points.

4.7.1.1. ACTIVATION

Activation was defined as the absorption of water by the seed and seed coat disruption. All seeds were evaluated for activation using a magnification lens. Activation data were presented as a percentage of the total seeds per sub-basket, by replicate, and by culture media (treatment).

4.7.1.2. MESOCOTYL EMERGENCE

Mesocotyl emergence was defined as the appearance of plant tissue in the form of shoots or roots from the germinated seed. Emergence data were presented as a percentage of the total germinated seeds per pot, by replicate, and by culture media (treatment) and as the time required for mesocotyl emergence expressed as the time to 30% emergence (ET30) in each replicate and treatment.

4.7.1.3. SEEDLING SURVIVAL

Survival only applied to seeds with emerged plant tissue. Mortality was defined as loss of living emerged plant tissue. Survival data were presented as a percentage of the total seeds with emerged plant tissue per basket, by replicate, and by culture media (treatment).

4.7.1.4. PHYTOTOXICITY (FREE LEAF PHASE)

Signs of phytotoxicity, including chlorosis of the leaves, darkening of the plant tissue (rot), wilting (loss of turgor pressure), and deformity were recorded and expressed as a percent of the seeds with emerged plant tissue. Because this endpoint was somewhat subjective and is a descriptive endpoint, peer-review was used to verify results.

4.7.2. DAY 0 TEST INITIATION AND SAMPLE COLLECTION

Treatment tanks were randomly assigned to a position in the exposure system in order to account for possible variations in temperature and light intensity. On study day 0, seeds selected for study were randomly placed in each pot such that five seeds were added to each pot in accordance with a randomized design chart until each sub-basket contained 40 seeds. Samples of the test solutions were collected and analyzed for parameters described in Table 3. Table 3 also provides an overview of the endpoints and the corresponding observation time points.

4.8. DATA ANALYSIS

All data from in-life portions of the study were tabulated in spreadsheets. The experimental unit for the present study was the replicate. For measurement endpoints (i.e., weights and lengths), replicate level data were based on the mean value for all plants measured in that replicate with the exception of the ET30 data sets which were based on median values. The statistical tests used to compare the culture media to the sulfide and B positive control differed depending on the data type and distribution for each measurement endpoint. For determination of concentration-based endpoints (NOEC and LOEC numerical endpoints), data that were expressed as a percent or proportion were transformed using the arcsine square root prior to further analysis. For measurement endpoints, comparisons between the treatments and designated controls were performed using one-way analysis of variance (ANOVA) or a nonparametric equivalent (KW-ANOVA). In all cases, sulfide treatments sharing the same iron concentration were compared against a control condition containing that same concentration of iron. When the initial test was statistically significant, *post hoc* tests were Dunnett's test for parametric test and Dunn's test for non-parametric tests. Treatment median ET30 values were determined by deriving the median of replicate ET30 values.

5. RESULTS

The statistical analyses and raw data: and Fort et al. 91) are presented as Appendices A and B, respectively. An assessment of study performance is provided in Table 6. The discussion below refers to nominal sulfide concentrations unless otherwise noted (e.g., in the case of sulfide loss as a function of iron concentration).

5.1. SULFIDE TOXICITY

A summary of water quality measurements, including mean measured sulfide concentrations, and study parameters for the negative controls (HS-1 with each Fe concentration), positive control (boron, as boric acid), and Fe-sulfide treatments is presented in Table 7. The pH was maintained at 6 to 7.5 s.u. in all replicates of controls and treatments, and ±0.5 s.u. within a given replicate for each daily measurement over the course of the study. DO levels were maintained at <2.0 mg/L in all treatments during the course of the study. Hydroponic chamber temperature was maintained at 21º ± 2ºC (day) and 12 ± 2ºC (night) in all replicates of control and treatments. A summary of sulfide concentrations based on time-weighted average values measured following test solution renewal (T0) and immediately prior to renewal (T24), along with an evaluation of 24-hour sulfide losses in each treatment is presented in Table 8. The mean sulfide concentration was calculated in accordance with OECD methods, and takes into account the variation in instantaneous concentration over time so that the area under the time-weighted mean is equal to the area under the concentration curve (6). Because the time intervals for all measurement periods were the same (i.e., 24 hours), the time-weighted mean values in Table 8 are equivalent to the arithmetic mean values for the newly prepared (post renewal) and 24-hour old (pre renewal) test solutions. Inter-replicate percent coefficient of variation (CV) within the control or a given sulfide exposure was ≤20% in both pre- and post-test solution renewal samples based on TWA concentrations. The inter-replicate CV for 24-hour sulfide loss based on the TWA concentration was ≤20%. Free sulfide loss between 24-hour renewals ranged from 22.3 to 29.7% in the 0.8 mg Fe/L treatments, and 40.2% to 58.6% in the 2.8 mg Fe/L treatments, respectively based on TWA measurements. The loss was presumably due in part to degradation, but primarily complexation with Fe. The results indicate that nominal and measured sulfide concentrations in freshly-prepared test solutions were very similar, but that increased Fe reduced free sulfide concentrations, and that this decrease was not necessarily a linear function of iron concentrations.

5.1.1. SULFIDE WITH 0.8 or 2.8 mg Fe/L

The effects of sulfide exposure on developing wild rice in the presence of 0.8 mg Fe/L are presented in Tables 8and 9. Overall, the following findings were noted:

- Decreased emergence and increased median ET30, and the occurrence of phytotoxicity were observed in wild rice exposed to 100 mg B/L relative to the HS-1 control with 0.8 mg Fe/L.
- Sulfide exposure did not affect seed activation, seedling survival, or induce phytotoxicity at 7.78 mg/L in either of the Fe treatments.

- Emergence was the most sensitive endpoint, with respective SD 10 NOEC and LOEC values of 1.56 mg/L and 3.12 mg/L sulfide for the 0.8 mg/L Fe treatment; and 3.12 and 7.78 mg Fe/L for the 2.8 mg/L Fe treatment.
- As observed in Fort et al. (1), the addition of 2.8 mg/L Fe reduced the toxicity (emergence) of sulfide indicating that the depth of hydroponic exposure during mesocotyl emergence and early growth was not a significant factor in the sensitivity of wild rice to sulfide. In the present study, a greater effect of Fe in reducing the effects of sulfide on mesocotyl emergence was noted at SD 10 compared to Fort et al. (1) based on NOEC and LOEC values, but the IC25 values were comparable.

6. PERFORMANCE CRITERIA AND VALIDITY

Results from the 00420 study met the performance criteria established (Table 6).

7. DISCUSSION

Results from this study indicate that for the most sensitive endpoint (mesocotyl emergence), exposure of developing wild rice to sulfide at concentrations ≥3.12 mg/L sulfide was toxic based on assessment of NOEC and LOEC values in the presence of 0.8 mg/L Fe. However, exposure of developing wild rice to sulfide at concentrations ≥7.8 mg/L was necessary to significantly reduce emergence in the presence of 2.8 mg Fe/L. Mesocotyl emergence was the most sensitive endpoint in the study, while seed activation, seedling survival, and phytotoxicity were the least sensitive endpoints. Based on measured sulfide concentrations, Fe reduced free sulfide concentrations in the 2.8 mg Fe/L treatment relative to the 0.8 mg Fe/L treatment. These observations, combined with differences in wild rice responses to sulfide across the different iron concentrations, demonstrate the ability of Fe to reduce sulfide toxicity to wild rice.

8. CONCLUSION

As observed in Fort et al. (1), the addition of 2.8 mg/L Fe reduced the toxicity (emergence) of sulfide indicating that the depth of hydroponic exposure during mesocotyl emergence and early growth was not a significant factor in the sensitivity of wild rice to sulfide. In the present study, a greater effect of Fe in reducing the effects of sulfide on mesocotyl emergence was noted at SD 10 compared to Fort et al. (1) based on NOEC and LOEC values, but the IC25 values were comparable. Results from these studies demonstrated that adequate oxygen was most likely not present at sufficient levels in the test media to support detoxification based on the hypoxic environment, complexation with Fe is the primary mitigating factor in terms of sulfide toxicity. Thus, the results suggest that detoxification of sulfide in the Fort et al. (1) were also the result of Fe complexation rather than detoxification by the plant itself.

9. REFERENCES

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TABLES

Table 2. Modified Hoagland's Solution – HS-1 with 1:4 Ammonia:Nitrate

Primary Ingredient	Media HS-1 (1:4) mL Stock/L
1 M NH_4H2PO_4	0.12
1 M NH_4NO_3	0.70
1 M KNO_3	1.10
1 M $Ca(NO_3)_2$	0.75
1M $MgSO_4$	0.50
Micronutrients (Stock B)	
0.556 g H_3BO_3	1.00
9.163 g $MnCl_2$ • 4 H2O	
0.219 g $ZnSO_4$ • 7 H2O	
0.077 g $CuSO_4$ • 5 H2O	
0.121 g Na_2MoO_4 • 2H2O	
2.417 g $FeCl_3$	

Table 3. Experimental Design[1]

Total Fe Concentration (mg/L)	Sulfide (mg/L)				
0.8 (HS-1)	0	0.3	1.56	3.1	7.8
2.8	0	0.3	1.56	3.1	7.8

[1] 100 mg B/L was also included with HS-1 only as a positive control.

Table 4. Experimental Conditions for Hydroponic Study – Definitive Phase

Test Substance		Sulfide (suspected toxicant) and Iron (suspected to interact with sulfide)
Test System (species)		*Zizania palustris* (wild rice)
Initial Stage		Seed
Exposure Period		10- d (mesocotyl emergence phase in dark)
Selection Criteria		Seed uniformity, visual quality, and activation
Exposure System		Static-renewal (daily) in controlled environmental chambers under anaerobic aquatic phase and aerobic vegetative phase
Exposure Route		Water (hydroponics)
Exchange frequency		Daily, 0.7 volumes/day
Water Source		Deionized water
Media		HS-1 with 1:4 ammonia:nitrate
Seed Density		40 seeds/1 L sub-basket (320 seeds per treatment or control)
Test Vessel		10 L chamber with 1 L basket equipped with mesh bottom supports for seeds
Replication		1 L baskets equipped with mesh bottom supports for seeds
Vessel Placement		Tanks are placed randomly throughout the experimental area
Positive Control		Boric Acid (100 mg B/L)
Test Performance Criteria (control)		See Table 6
Test Endpoints	Daily	Activation, mesocotyl emergence, seedling survival, and visual inspection of development (emergence and normalcy of development)
	SD 10	Activation, mesocotyl emergence (%), survival, leaf number, and signs of phytotoxicity
Feeding	Nutrient/Micronutrients	HS-1 modified with 1:4 ammonia:nitrate and either 0.8 or 2.8 mg Fe/L
	Frequency	Daily, 0.7 volumes renewed
Lighting	Photoperiod	None
Temperature		In all replicates, daily, 21º ± 2ºC (day), and nightly, 12 ± 2ºC (night)
pH, ORP, DO, and sulfide		2x per day in all replicates prior to and following renewal
Conductivity, alkalinity, hardness, ammonia, total Fe, nitrate, sulfate, phosphate, total residual oxidants		Initiation (SD 0), SD 7, and SD 10.

Table 5. Observation Time Points for Primary Endpoints

Endpoints:	Daily	SD 10 Emergence Phase
Activation	●	●
Survival	●	●
Emergence	●	●
Phytotoxicity		●

Table 6. General Test Performance Criteria

Criterion	Criterion	Acceptance (value, if appropriate)
Control activation	95%	√ (100%)
Control mesocotyl emergence	≥30% on SD 10	√ (30.6 and 32.5% in the 0.8 and 2.8 mg/L Fe controls)
Control survival	≥90%	√ (100%)
Positive control (BA) phytotoxicity	≥80%	√ (100%)
DO	<2.0 mg/L	√ (within range)
pH	6-7.5 in all replicates of control and treatments and ±0.5 s.u. within a given replicate for each daily measurement point at T0 and T24 and over the course of the study in a given replicate	√ (within range)
Water temperature	21° ± 2ºC (day), and nightly, 12 ± 2ºC (night) in all replicates of control and treatments	√ (within range)
Sulfide concentration	Inter-replicate CV ≤20% within each control or treatment condition at pre- or post-renewal time points based on TWA concentration; and ≤30% 24-hour sulfide loss in 0.8 mg Fe/L set (control) based on TWA concentration	√ (within range)

Table 7. Water Quality Summary

	Temp (ºC)		Light Intensity (lux)	pH		DO				ORP		Sulfide (mg/L)		
						Headspace		Aquatic						
	AM	PM		Pre-Renew	Post-Renew	Pre	Post	Pre	Post	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	% Loss
	HS-1 (1:4) Nutrient Media													
MIN	22.3	12.3		6.9	6.9	6.9	7.0	0.5	0.2	50.8	52.8	<0.01[1]	<0.01	-
MAX	22.8	13.1		7.1	7.1	7.9	7.8	0.9	0.9	57.3	58.1	<0.01	<0.01	-
MEAN	22.5	12.7		7.0	7.0	7.5	7.5	0.7	0.7	54.0	55.3	<0.01	<0.01	N/A
SEM	0.02	0.03		0.01	0.01	0.04	0.03	0.02	0.02	0.17	0.19	0.000	0.000	-
	100 mg/L Boric Acid Treatment													
MIN	22.4	12.2		6.9	6.8	6.9	6.9	0.5	0.5	52.2	52.7	<0.01	<0.01	-
MAX	22.9	13.1		7.0	7.0	8.0	7.9	0.9	0.9	57.3	59.4	<0.01	<0.01	-
MEAN	22.5	12.7		6.9	6.9	7.5	7.6	0.7	0.7	54.7	55.9	<0.01	<0.01	N/A
SEM	0.02	0.03		0.01	0.01	0.04	0.04	0.02	0.02	0.22	0.25	0.000	0.000	-
	0.3 mg/L Sulfide 0.8 mg/L Fe													
MIN	22.3	12.4		6.8	6.7	6.9	6.9	0.5	0.5	120.8	122.2	<0.01	0.28	-
MAX	22.9	13.0		7.0	7.1	7.9	7.9	0.9	0.9	130.2	136.2	0.31	0.43	-
MEAN	22.5	12.7		6.9	6.8	7.5	7.6	0.8	0.7	126.2	128.3	0.26	0.37	29.7
SEM	0.02	0.02		0.01	0.01	0.04	0.04	0.02	0.02	0.31	0.46	0.013	0.004	-
	1.56 mg/L Sulfide 0.8 mg/L Fe													
MIN	22.3	12.3		6.7	6.6	6.9	7.1	0.4	0.4	129.7	131.1	<0.01	1.30	-
MAX	22.8	13.1		6.9	6.9	7.9	7.9	0.9	0.9	138.1	142.8	1.58	1.88	-
MEAN	22.5	12.7		6.8	6.8	7.5	7.5	0.7	0.7	133.6	136.0	1.26	1.64	23.2
SEM	0.02	0.03		0.01	0.01	0.03	0.03	0.02	0.02	0.30	0.39	0.062	0.019	-
	3.12 mg/L Sulfide 0.8 mg/L Fe													
MIN	22.3	12.3		6.5	6.5	6.9	7.0	0.5	0.5	140.1	142.1	<0.01	1.75	-
MAX	22.7	13.1		6.9	6.8	8.2	7.9	0.9	0.9	144.9	150.8	2.79	3.75	-
MEAN	22.5	12.7		6.7	6.7	7.5	7.6	0.7	0.7	142.3	144.5	2.31	3.20	27.8
SEM	0.02	0.03		0.01	0.01	0.04	0.04	0.02	0.02	0.20	0.27	0.113	0.055	-

[1] Limit of quantitation (LOQ) = 0.01 mg/L.

	Temp (ºC)		Light Intensity (lux)	pH		DO				ORP		Sulfide (mg/L)		
						Headspace		Aquatic						
	AM	PM		Pre-Renew	Post-Renew	Pre	Post	Pre	Post	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	% Loss
	7.8 mg/L Sulfide 0.8 mg/L Fe													
MIN	22.3	12.4		6.5	6.4	7.0	7.0	0.5	0.4	150.8	150.4	<0.01	7.13	-
MAX	23.0	13.1		6.8	6.7	7.9	7.9	0.9	0.9	156.5	157.8	8.08	8.60	-
MEAN	22.5	12.7		6.6	6.5	7.6	7.6	0.7	0.7	152.8	154.5	5.83	7.71	24.4
SEM	0.02	0.03		0.01	0.01	0.03	0.04	0.02	0.02	0.26	0.28	0.296	0.051	-
	HS-1 (1:4) Nutrient Media 2.8 mg/L Fe													
MIN	22.3	12.4		6.9	6.6	6.8	7.0	0.5	0.3	52.3	53.7	<0.01	<0.01	-
MAX	23.1	13.2		7.1	7.1	7.9	7.9	0.9	0.9	56.5	57.4	<0.01	<0.01	-
MEAN	22.5	12.7		7.0	6.9	7.5	7.5	0.8	0.7	54.2	55.5	<0.01	<0.01	N/A
SEM	0.02	0.03		0.01	0.01	0.04	0.03	0.02	0.02	0.15	0.19	0.000	0.000	-
	0.3 mg/L Sulfide 2.8 mg/L Fe													
MIN	22.3	12.4		6.8	6.7	6.9	6.8	0.5	0.5	121.6	122.8	<0.01	0.31	-
MAX	23.0	13.1		6.9	6.9	7.9	7.9	0.9	0.9	130.9	136.3	0.25	0.43	-
MEAN	22.5	12.8		6.9	6.8	7.6	7.5	0.7	0.7	126.5	128.9	0.21	0.37	43.2
SEM	0.03	0.03		0.01	0.01	0.04	0.04	0.02	0.02	0.31	0.43	0.010	0.004	-
	1.56 mg/L Sulfide 2.8 mg/L Fe													
MIN	22.3	12.4		6.7	6.6	7.1	7.0	0.5	0.4	130.4	131.6	<0.01	1.48	-
MAX	22.9	13.1		6.9	6.8	7.8	7.9	0.9	0.9	137.2	142.9	1.20	1.87	-
MEAN	22.5	12.7		6.8	6.7	7.5	7.6	0.7	0.7	133.7	136.6	0.98	1.64	40.2
SEM	0.02	0.03		0.01	0.01	0.03	0.03	0.02	0.02	0.29	0.41	0.048	0.015	-
	3.12 mg/L Sulfide 2.8 mg/L Fe													
MIN	22.3	12.3		6.6	6.5	7.2	7.0	0.5	0.5	138.1	140.6	<0.01	2.99	-
MAX	23.1	13.1		6.8	6.8	7.9	7.9	0.9	0.9	146.1	150.9	1.74	3.72	-
MEAN	22.5	12.7		6.7	6.6	7.6	7.5	0.7	0.8	142.6	145.2	1.37	3.31	58.6
SEM	0.02	0.03		0.01	0.01	0.03	0.03	0.02	0.02	0.25	0.38	0.069	0.029	-
	7.8 mg/L Sulfide 2.8 mg/L Fe													
MIN	22.2	12.3		6.5	6.4	6.9	7.2	0.5	0.5	150.0	150.8	<0.01	6.86	-
MAX	22.9	13.0		6.7	6.7	7.9	7.9	0.9	0.9	156.9	158.2	4.67	8.37	-
MEAN	22.5	12.7		6.6	6.5	7.6	7.6	0.8	0.7	153.4	155.0	3.77	7.53	49.9
SEM	0.02	0.03		0.01	0.01	0.04	0.03	0.02	0.02	0.29	0.30	0.186	0.063	-

Table 8. Study Day 10 Endpoint Summary

Treatment	Rep	Per Replicate								
		Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emergence (%)	Seedling Survival (n)	Survival (%)	Mean Free Leaf (n)	Phytotox: Abnormal Appearance (n)	Phytotox: Abnormal Appearance (%)
HS-1[1]	A	40	100.0	12	30.0	12.0	100.0		0	0.0
	B	40	100.0	10	25.0	10.0	100.0		0	0.0
	C	40	100.0	13	32.5	13.0	100.0		0	0.0
	D	40	100.0	14	35.0	14.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**12.3**	**30.6**	**12.3**	**100.0**		**0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.85**	**2.13**	**0.85**	**0.0**		**0.0**	**0.0**
100 mg/L BA	A1	40	100.0	3	7.5	3.0	100.0		3	100.0
	A2	40	100.0	4	10.0	4.0	100.0		4	100.0
	B1	40	100.0	4	10.0	4.0	100.0		4	100.0
	B2	40	100.0	3	7.5	3.0	100.0		3	100.0
	Mean:	**40**	**100.0**	**3.5**	**8.8**	**3.5**	**100.0**		**3.5**	**100.0**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**		**0.3**	**0.0**
0.3 mg/L S^{2-}	A	40	100.0	14	35.0	14.0	100.0		0	0.0
	B	40	100.0	10	25.0	10.0	100.0		0	0.0
	C	40	100.0	12	30.0	12.0	100.0		0	0.0
	D	40	100.0	13	32.5	13.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**12.3**	**30.6**	**12.3**	**100**		**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.85**	**2.13**	**0.85**	**0.0**		**0.00**	**0.0**
1.56 mg/L S^{2-}	A1	40	100.0	12	30.0	12.0	100.0		0	0.0
	A2	40	100.0	13	32.5	13.0	100.0		0	0.0
	B1	40	100.0	12	30.0	12.0	100.0		0	0.0
	B2	40	100.0	10	25.0	10.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**11.8**	**29.4**	**11.8**	**100**		**0**	**0**
	SEM:	**0.0**	**0.0**	**0.63**	**1.57**	**0.63**	**0.0**		**0.0**	**0.0**

[1] Contains 0.8 mg Fe/L. Statistical comparisons made to HS-1 with 0.8 Fe/L treatment set analyzed to hold the nominal Fe constant during analysis.

Table 8. Study Day 10 Endpoint Summary *(Continued)*

Treatment	Rep	Per Replicate								
		Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emergence (%)	Seedling Survival (n)	Survival (%)	Mean Free Leaf (n)	Phytotox: Abnormal Appearance (n)	Phytotox: Abnormal Appearance (%)
3.12 mg/L S^{2-}	A	40	100.0	8	20.0	8.0	100.0		0	0.0
	B	40	100.0	9	22.5	9.0	100.0		0	0.0
	C	40	100.0	8	20.0	8.0	100.0		0	0.0
	D	40	100.0	9	22.5	9.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**8.5**[1]	**21.3**	**8.5**	**100**		**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**		**0.00**	**0.0**
7.8 mg/L S^{2-}	A1	40	100.0	4	10.0	4.0	100.0		0	0.0
	A2	40	100.0	4	10.0	4.0	100.0		0	0.0
	B1	40	100.0	3	7.5	3.0	100.0		0	0.0
	B2	40	100.0	4	10.0	4.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**3.8**[1]	**9.4**	**3.8**	**100.0**		**0.0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.25**	**0.63**	**0.25**	**0.0**		**0.00**	**0.0**
HS-1 2.8 mg/L Fe[2]	A	40	100.0	12	30.0	12.0	100.0		0	0.0
	B	40	100.0	14	35.0	14.0	100.0		0	0.0
	C	40	100.0	15	37.5	15.0	100.0		0	0.0
	D	40	100.0	11	27.5	11.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**13.0**	**32.5**	**13.0**	**100**		**0**	**0**
	SEM:	**0.0**	**0.0**	**0.91**	**2.28**	**0.91**	**0.0**		**0.0**	**0.0**
0.3 mg/L S^{2-} 2.8 mg/L Fe	A1	40	100.0	12	30.0	12.0	100.0		0	0.0
	A2	40	100.0	14	35.0	14.0	100.0		0	0.0
	B1	40	100.0	13	32.5	13.0	100.0		0	0.0
	B2	40	100.0	12	30.0	12.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**12.8**	**31.9**	**12.8**	**100**		**0**	**0**
	SEM:	**0.0**	**0.0**	**0.48**	**1.20**	**0.48**	**0.0**		**0.0**	**0.0**

[1] Significantly less than 0.8 mg/L Fe HS-1 control (ANOVA, Dunnett's test, $p<0.05$).
[2] Contains 2.8 mg Fe/L. Statistical comparisons made to HS-1 with 2.8 Fe/L treatment set analyzed to hold the nominal Fe constant during analysis.

Table 8. Study Day 10 Endpoint Summary *(Continued)*

Treatment	Rep	Per Replicate: Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emergence (%)	Seedling Survival (n)	Survival (%)	Mean Free Leaf (n)	Phytotox: Abnormal Appearance (n)	(%)
1.56 mg/L S^{2-} 2.8 mg/L Fe	A	40	100.0	10	25.0	10.0	100.0		0	0.0
	B	40	100.0	10	25.0	10.0	100.0		0	0.0
	C	40	100.0	9	22.5	9.0	100.0		0	0.0
	D	40	100.0	9	22.5	9.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**9.5**	**23.8**	**9.5**	**100**		**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**		**0.00**	**0.0**
3.12 mg/L S^{2-} 2.8 mg/L Fe	A1	40	100.0	12	30.0	12.0	100.0		0	0.0
	A2	40	100.0	12	30.0	12.0	100.0		0	0.0
	B1	40	100.0	13	32.5	13.0	100.0		0	0.0
	B2	40	100.0	11	27.5	11.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**12.0**	**30.0**	**12.0**	**100.0**		**0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.41**	**1.02**	**0.41**	**0.0**		**0.0**	**0.0**
7.8 mg/L S^{2-} 2.8 mg/L Fe	A	40	100.0	7	17.5	7.0	100.0		0	0.0
	B	40	100.0	7	17.5	7.0	100.0		0	0.0
	C	40	100.0	8	20.0	8.0	100.0		0	0.0
	D	40	100.0	7	17.5	7.0	100.0		0	0.0
	Mean:	**40**	**100.0**	**7.3**[1]	**18.1**	**7.3**	**100**		**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.25**	**0.63**	**0.25**	**0.0**		**0.00**	**0.0**

Table 9. Time to 30% Emergence in Wild Rice on SD10[2]

	Median Emergence Time (d)										
	HS-1	100 mg/L BA	0.3 mg/L S^{2-} 0.8 mg/L Fe	1.56 mg/L S^{2-} 0.8 mg/L Fe	3.12 mg/L S^{2-} 0.8 mg/L Fe	7.8 mg/L S^{2-} 0.8 mg/L Fe	HS-1 2.8 mg/L Fe	0.3 mg/L S^{2-} 2.8 mg/L Fe	1.56 mg/L S^{2-} 2.8 mg/L Fe	3.12 mg/L S^{2-} 2.8 mg/L Fe	7.8 mg/L S^{2-} 2.8 mg/L Fe
Rep A	7	>10	6	7	>10	>10	7	7	>10	8	>10
Rep B	>10	>10	6	6	>10	>10	6	6	>10	8	>10
Rep C	7	>10	>10	7	>10	>10	6	7	>10	8	>10
Rep D	6	>10	7	>10	>10	>10	>10	7	>10	>10	>10
Median	**7**	**>10**	**6.5**	**7**	**>10**	**>10**	**6.5**	**7**	**>10**	**8**	**>10**

[1] Significantly less than 2.8 mg/L Fe HS-1 control (KW-ANOVA, Dunn's test, $p<0.05$).
[2] Based on time (in days) required to achieve 30% emergence.

Appendix A. Raw Data and Statistical Analyses

Tier 1 Parameters

HS-1 (1:4) 0.8 mg/L Fe

IMAM01-00420

								Headspace DO		Aquatic DO				Sulfide,		Sulfide,		
Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	Pre-Renew ORP	Post-Renew ORP	mV Reading (mV)	Calc Conc (mg/L)	mV Reading (mV)	Calc Conc (mg/L)	Comments/Observations
0	A	22.2		12.8			7.0		7.8		0.6		56.3	0.0	0.0	0.0	0.0	
	B	22.3		12.6			7.1		7.0		0.4		53.9	0.0	0.0	0.0	0.0	
	C	22.4		12.6			7.0		7.7		0.8		57.1	0.0	0.0	0.0	0.0	
	D	22.4		12.6			7.1		7.4		0.6		56.9	0.0	0.0	0.0	0.0	
1	A	22.4	22.5	13.1		7.1	7.0	7.8	7.4	0.8	0.7	54.2	53.8	0.0	0.0	0.0	0.0	
	B	22.4	22.3	12.5		7.0	7.0	7.7	7.6	0.8	0.7	53.9	54.8	0.0	0.0	0.0	0.0	
	C	22.4	22.5	12.8		7.0	7.0	7.6	7.7	0.8	0.9	54.5	54.8	0.0	0.0	0.0	0.0	
	D	22.5	22.6	12.5		7.0	7.1	7.9	7.7	0.6	0.7	52.9	53.8	0.0	0.0	0.0	0.0	
2	A	22.4	22.5	12.4		7.0	7.1	7.3	7.5	0.7	0.9	54.2	55.8	0.0	0.0	0.0	0.0	
	B	22.4	22.3	12.5		7.1	7.0	7.3	7.3	0.5	0.7	54.5	56.9	0.0	0.0	0.0	0.0	
	C	22.6	22.5	13.0		7.0	7.1	7.3	7.4	0.7	0.8	54.6	55.9	0.0	0.0	0.0	0.0	
	D	22.6	22.6	12.9		7.0	7.0	7.8	7.6	0.8	0.6	54.3	56.9	0.0	0.0	0.0	0.0	
3	A	22.5	22.4	12.5		7.0	7.0	7.6	7.7	0.8	0.9	54.6	55.5	0.0	0.0	0.0	0.0	
	B	22.7	22.6	12.9		7.0	6.9	7.7	7.6	0.9	0.8	53.9	54.1	0.0	0.0	0.0	0.0	
	C	22.5	22.4	12.6		7.0	7.1	7.4	7.6	0.8	0.6	54.6	55.8	0.0	0.0	0.0	0.0	
	D	22.5	22.6	12.5		7.1	7.0	7.7	7.5	0.7	0.5	55.8	57.2	0.0	0.0	0.0	0.0	
4	A	22.5	22.8	12.6		7.0	7.0	7.5	7.7	0.8	0.6	54.2	55.1	0.0	0.0	0.0	0.0	
	B	22.5	22.5	12.9		7.0	6.9	7.4	7.2	0.5	0.6	57.3	58.1	0.0	0.0	0.0	0.0	
	C	22.6	22.4	12.7		7.0	6.9	7.6	7.3	0.8	0.9	54.2	55.6	0.0	0.0	0.0	0.0	
	D	22.6	22.5	12.7		7.0	6.9	7.8	7.7	0.5	0.7	55.1	57.2	0.0	0.0	0.0	0.0	
5	A	22.3	22.4	12.8		7.0	7.0	6.9	7.3	0.8	0.9	53.5	54.1	0.0	0.0	0.0	0.0	
	B	22.4	22.6	12.7		7.0	6.9	7.6	7.8	0.9	0.8	53.7	54.7	0.0	0.0	0.0	0.0	
	C	22.5	22.6	12.8		7.0	6.9	7.4	7.5	0.7	0.8	54.4	55.3	0.0	0.0	0.0	0.0	
	D	22.4	22.5	12.4		7.1	7.0	7.5	7.6	0.7	0.6	54.8	55.6	0.0	0.0	0.0	0.0	
6	A	22.5	22.6	12.8		7.1	7.0	6.9	7.3	0.7	0.6	54.2	55.5	0.0	0.0	0.0	0.0	
	B	22.5	22.4	12.8		6.9	6.9	7.6	7.5	0.7	0.9	55.1	56.1	0.0	0.0	0.0	0.0	
	C	22.5	22.4	12.8		7.0	7.0	7.4	7.4	0.8	0.7	52.5	54.7	0.0	0.0	0.0	0.0	
	D	22.7	22.4	12.5		7.0	6.9	7.3	7.5	0.5	0.6	53.9	55.6	0.0	0.0	0.0	0.0	
7	A	22.5	22.4	12.9		7.0	7.0	7.6	7.5	0.8	0.7	54.2	56.1	0.0	0.0	0.0	0.0	
	B	22.6	22.5	12.5		7.0	7.0	7.8	7.6	0.7	0.8	54.1	55.5	0.0	0.0	0.0	0.0	
	C	22.6	22.5	12.9		7.0	7.0	7.6	7.3	0.8	0.7	54.5	54.9	0.0	0.0	0.0	0.0	
	D	22.5	22.5	12.6		7.0	6.9	7.4	7.8	0.8	0.8	52.1	53.6	0.0	0.0	0.0	0.0	
8	A	22.6	22.5	12.9		7.0	7.0	7.6	7.3	0.8	0.6	54.1	55.5	0.0	0.0	0.0	0.0	
	B	22.6	22.4	12.6		7.1	7.0	7.7	7.8	0.8	0.6	53.8	54.1	0.0	0.0	0.0	0.0	
	C	22.5	22.6	12.8		7.0	7.0	7.6	7.8	0.9	0.2	52.6	53.9	0.0	0.0	0.0	0.0	
	D	22.6	22.5	12.5		7.0	6.9	7.4	7.6	0.9	0.7	51.9	54.1	0.0	0.0	0.0	0.0	
9	A	22.5	22.4	12.6		7.0	7.0	7.6	7.3	0.8	0.9	54.3	54.8	0.0	0.0	0.0	0.0	
	B	22.4	22.4	12.3		7.1	7.0	7.4	7.1	0.7	0.5	53.8	54.5	0.0	0.0	0.0	0.0	
	C	22.6	22.4	12.8		7.0	7.0	7.6	7.5	0.6	0.8	53.7	54.1	0.0	0.0	0.0	0.0	
	D	22.4	22.5	12.5		7.1	7.0	7.6	7.4	0.6	0.9	50.8	52.8	0.0	0.0	0.0	0.0	
10	A	22.5	22.4			7.0		7.5		0.8		53.6		0.0	0.0	0.0	0.0	
	B	22.5	22.5			7.1		7.7		0.6		52.8		0.0	0.0	0.0	0.0	
	C	22.4	22.5			7.0		7.3		0.6		54.2		0.0	0.0	0.0	0.0	
	D	22.5	22.4			6.9		7.1		0.7		54.8		0.0	0.0	0.0	0.0	
	MIN	22.2	22.3	12.3	0	6.9	6.9	6.9	7.0	0.5	0.2	50.8	52.8	0.0	0.00	0.0	0.00	
	MAX	22.7	22.8	13.1	0	7.1	7.1	7.9	7.8	0.9	0.9	57.3	58.1	0.0	0.00	0.0	0.00	
	MEAN	22.5	22.5	12.7	N/A	7.0	7.0	7.5	7.5	0.7	0.7	54.0	55.3	0.0	0.00	0.0	0.00	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.04	0.03	0.02	0.02	0.17	0.19	0.00	0.000	0.00	0.000	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters
0.3 mg/L S2- 0.8 mg/L Fe

IMAM01-00420

								Headspace DO		Aquatic DO				Sulfide,		Sulfide,		
Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	Pre-Renew ORP	Post-Renew ORP	mV Reading (mV)	Calc Conc (mg/L)	mV Reading (mV)	Calc Conc (mg/L)	Comments/Observations
0	A	22.3		12.9			6.9		7.6		0.7		132.5	0.0	0.0	724.2	0.335	
	B	22.2		12.4			6.9		6.9		0.6		136.2	0.0	0.0	723.3	0.311	
	C	22.3		12.4			6.9		7.5		0.7		130.5	0.0	0.0	722.2	0.284	
	D	22.5		12.7			6.9		7.8		0.8		133.1	0.0	0.0	723.6	0.319	
1	A	22.5	22.3	12.8		6.9	6.8	7.9	7.6	0.6	0.7	126.3	130.1	721.3	0.30	724.9	0.39	
	B	22.5	22.4	12.8		6.9	6.8	7.8	7.8	0.9	0.6	125.2	127.6	720.7	0.28	725.1	0.40	
	C	22.3	22.6	12.9		6.9	6.8	7.5	7.8	0.7	0.6	127.5	129.3	721.7	0.30	724.2	0.37	
	D	22.6	22.7	12.6		6.9	7.0	7.7	7.8	0.8	0.9	128.1	130.9	721.2	0.29	724.6	0.38	
2	A	22.5	22.4	12.6		6.9	6.8	7.5	7.7	0.8	0.6	125.7	126.9	720.3	0.27	724.5	0.38	
	B	22.5	22.4	12.6		6.9	6.9	7.2	7.2	0.8	0.6	127.3	128.9	720.7	0.28	725.1	0.40	
	C	22.5	22.5	12.8		6.9	6.8	7.5	7.6	0.9	0.8	127.2	129.6	721.2	0.29	724.2	0.37	
	D	22.5	22.5	13.0		6.8	6.7	7.5	7.5	0.9	0.5	125.6	127.5	721.2	0.29	724.2	0.37	
3	A	22.6	22.5	12.6		6.9	6.8	7.5	7.8	0.7	0.6	128.3	130.1	720.1	0.27	724.2	0.38	
	B	22.5	22.5	12.8		6.9	6.8	7.9	7.7	0.7	0.6	127.5	129.6	720.7	0.29	725.1	0.40	
	C	22.6	22.5	12.8		6.9	6.8	7.5	7.7	0.7	0.5	123.9	124.1	721.0	0.29	724.2	0.38	
	D	22.6	22.8	12.7		6.9	6.8	7.8	7.6	0.9	0.8	120.8	123.6	721.3	0.30	723.6	0.36	
4	A	22.6	22.9	12.9		6.9	6.8	7.8	7.5	0.9	0.5	125.6	126.7	720.4	0.28	724.0	0.37	
	B	22.6	22.6	12.7		6.9	6.9	7.9	7.9	0.9	0.7	123.9	125.6	720.7	0.29	725.1	0.40	
	C	22.5	22.5	12.5		6.9	6.8	7.7	7.5	0.7	0.8	126.9	127.2	721.5	0.30	724.2	0.37	
	D	22.5	22.4	12.8		6.9	6.8	7.9	7.6	0.6	0.8	125.1	128.1	721.3	0.30	723.2	0.35	
5	A	22.4	22.4	12.7		6.9	6.8	7.2	7.4	0.9	0.8	126.5	127.4	720.1	0.27	724.2	0.37	
	B	22.5	22.5	12.5		6.8	6.7	7.3	7.0	0.8	0.7	125.2	127.2	720.7	0.29	725.5	0.41	
	C	22.4	22.5	12.9		6.9	6.8	7.3	7.4	0.6	0.9	128.1	130.3	721.2	0.30	724.2	0.37	
	D	22.5	22.6	12.6		6.9	6.8	7.3	7.7	0.5	0.6	129.1	131.1	721.3	0.30	723.2	0.35	
6	A	22.3	22.5	12.7		7.0	7.1	7.2	7.4	0.5	0.7	123.5	125.5	720.3	0.27	724.2	0.36	
	B	22.4	22.5	12.6		6.8	6.7	7.4	7.6	0.8	0.7	126.4	128.7	720.7	0.28	725.3	0.40	
	C	22.4	22.3	12.7		6.9	6.9	7.5	7.5	0.8	0.6	123.1	124.5	721.4	0.29	724.2	0.36	
	D	22.7	22.5	12.5		6.9	6.8	7.2	7.6	0.7	0.8	122.6	124.7	721.3	0.29	723.4	0.34	
7	A	22.5	22.4	12.8		6.9	6.9	7.7	7.4	0.9	0.6	128.3	129.5	720.4	0.28	724.1	0.37	
	B	22.5	22.6	12.6		6.8	6.7	7.5	7.2	0.9	0.8	126.9	131.6	720.7	0.28	725.3	0.40	
	C	22.5	22.5	12.7		7.0	7.0	7.5	7.4	0.6	0.9	126.1	128.3	721.2	0.29	724.0	0.36	
	D	22.6	22.5	12.7		6.8	6.7	7.6	7.9	0.7	0.6	128.4	132.9	721.5	0.30	723.4	0.35	
8	A	22.7	22.6	12.8		6.9	6.8	7.7	7.8	0.9	0.7	126.5	127.1	720.1	0.27	724.4	0.38	
	B	22.7	22.5	12.8		6.8	6.9	7.6	7.4	0.9	0.7	127.1	128.4	720.7	0.28	725.5	0.41	
	C	22.6	22.5	12.7		6.9	6.9	7.7	7.5	0.8	0.9	123.6	122.2	721.0	0.29	724.0	0.37	
	D	22.5	22.5	12.8		6.9	6.8	7.5	7.5	0.8	0.8	126.5	124.9	721.5	0.30	723.4	0.35	
9	A	22.4	22.4	12.5		6.9	6.9	7.7	7.5	0.7	0.8	128.6	127.2	720.1	0.27	724.6	0.38	
	B	22.5	22.5	12.5		6.9	6.8	7.6	7.8	0.8	0.9	126.2	127.5	720.7	0.28	725.5	0.41	
	C	22.5	22.3	12.7		6.9	6.9	7.7	7.4	0.5	0.7	125.1	124.6	721.0	0.29	724.3	0.37	
	D	22.3	22.3	12.4		6.9	6.9	7.5	7.7	0.7	0.5	124.6	128.3	721.5	0.30	723.4	0.34	
10	A	22.4	22.5			6.9		7.3		0.7		130.2		720.0	0.28	724.2	0.38	
	B	22.4	22.5			6.9		7.8		0.5		127.6		720.3	0.28	725.5	0.43	
	C	22.5	22.6			6.9		7.4		0.7		125.9		721.3	0.31	724.5	0.39	
	D	22.6	22.5			6.8		6.9		0.8		126.8		721.1	0.30	723.4	0.36	
	MIN	22.2	**22.3**	**12.4**	**0**	**6.8**	**6.7**	**6.9**	**6.9**	**0.5**	**0.5**	**120.8**	**122.2**	**0.0**	**0.00**	**722.2**	**0.28**	
	MAX	22.7	**22.9**	**13.0**	**0**	**7.0**	**7.1**	**7.9**	**7.9**	**0.9**	**0.9**	**130.2**	**136.2**	**721.7**	**0.31**	**725.5**	**0.43**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.9**	**6.8**	**7.5**	**7.6**	**0.8**	**0.7**	**126.2**	**128.3**	**655.4**	**0.26**	**724.3**	**0.37**	
	SEM	0.02	0.02	0.02	N/A	0.01	0.01	0.04	0.04	0.02	0.02	0.31	0.46	31.60	0.013	0.11	0.004	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

FEL

Tier 1 Parameters

1.56 mg/L S2- 0.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.4		13.0			6.8		7.5		0.9		137.1	0.0	0.0	744.5	1.74	
	B	22.4		12.8			6.8		7.3		0.5		140.5	0.0	0.0	740.9	1.30	
	C	22.3		12.8			6.8		7.6		0.7		136.9	0.0	0.0	742.7	1.50	
	D	22.4		12.8			6.8		7.9		0.8		139.8	0.0	0.0	741.4	1.35	
1	A	22.3	22.4	12.9		6.8	6.8	7.5	7.3	0.9	0.8	134.9	136.4	742.8	1.58	744.9	1.86	
	B	22.3	22.3	13.0		6.8	6.8	7.5	7.7	0.7	0.8	133.1	136.8	741.6	1.44	742.9	1.59	
	C	22.1	22.5	12.7		6.8	6.8	7.4	7.3	0.6	0.8	133.8	135.4	740.2	1.29	743.0	1.60	
	D	22.5	22.5	12.6		6.8	6.9	7.5	7.6	0.8	0.8	135.7	137.4	740.6	1.33	743.4	1.65	
2	A	22.5	22.4	12.6		6.8	6.7	7.2	7.3	0.8	0.5	132.1	133.3	742.5	1.56	744.9	1.88	
	B	22.5	22.4	12.5		6.8	6.8	7.4	7.5	0.7	0.5	134.8	136.9	741.6	1.45	742.7	1.58	
	C	22.7	22.6	12.9		6.8	6.9	7.7	7.5	0.6	0.7	134.5	138.7	740.2	1.30	743.0	1.62	
	D	22.7	22.5	12.7		6.8	6.7	7.3	7.4	0.8	0.7	132.8	134.1	740.4	1.32	743.0	1.62	
3	A	22.5	22.5	12.7		6.8	6.7	7.7	7.9	0.7	0.8	135.6	137.2	742.5	1.56	744.9	1.88	
	B	22.6	22.5	12.7		6.8	6.7	7.5	7.6	0.8	0.7	132.8	133.8	741.2	1.41	742.7	1.58	
	C	22.4	22.6	13.0		6.8	6.8	7.8	7.5	0.4	0.6	134.6	135.9	740.2	1.30	743.2	1.65	
	D	22.4	22.5	12.9		6.8	6.7	7.4	7.8	0.7	0.6	129.7	131.1	740.6	1.35	743.0	1.62	
4	A	22.4	22.7	12.8		6.8	6.7	7.3	7.4	0.7	0.7	133.9	134.9	742.1	1.49	744.9	1.84	
	B	22.6	22.7	12.7		6.8	6.7	7.6	7.5	0.8	0.9	134.7	137.3	741.2	1.39	742.7	1.56	
	C	22.6	22.6	12.3		6.8	6.7	7.3	7.4	0.6	0.9	131.4	133.5	740.3	1.29	743.1	1.61	
	D	22.6	22.5	12.9		6.8	6.7	7.6	7.8	0.9	0.8	135.8	137.4	740.6	1.32	743.0	1.59	
5	A	22.5	22.5	13.0		6.8	6.8	7.3	7.2	0.8	0.7	133.8	134.7	742.3	1.51	744.7	1.81	
	B	22.3	22.6	12.6		6.8	6.7	7.4	7.2	0.7	0.8	136.8	140.9	741.2	1.39	742.7	1.56	
	C	22.3	22.4	12.5		6.8	6.7	7.5	7.6	0.7	0.8	134.8	135.2	740.3	1.29	743.4	1.64	
	D	22.7	22.7	12.7		6.8	6.8	7.8	7.5	0.7	0.8	135.8	142.8	740.7	1.33	743.2	1.62	
6	A	22.5	22.4	12.8		6.8	6.7	7.3	7.5	0.6	0.9	133.6	134.6	742.3	1.49	744.7	1.79	
	B	22.4	22.5	12.5		6.7	6.7	7.5	7.3	0.9	0.7	132.6	135.1	741.4	1.39	742.7	1.54	
	C	22.6	22.5	12.8		6.8	6.7	7.4	7.8	0.7	0.4	132.8	133.6	740.3	1.27	743.6	1.65	
	D	22.8	22.4	12.4		6.8	6.8	7.4	7.3	0.5	0.6	134.7	136.9	740.5	1.29	743.2	1.60	
7	A	22.6	22.5	13.1		6.8	6.8	7.8	7.6	0.7	0.8	134.5	136.4	742.3	1.50	744.3	1.75	
	B	22.6	22.5	12.7		6.7	6.7	6.9	7.1	0.6	0.7	130.8	133.8	741.6	1.42	742.7	1.54	
	C	22.6	22.5	13.0		6.9	6.8	7.6	7.5	0.8	0.5	131.1	134.5	740.3	1.28	743.3	1.62	
	D	22.6	22.5	12.9		6.8	6.7	7.8	7.5	0.8	0.9	131.6	135.8	740.7	1.32	743.2	1.61	
8	A	22.5	22.8	12.9		6.8	6.7	7.5	7.4	0.6	0.8	138.1	139.5	742.2	1.50	744.3	1.76	
	B	22.5	22.6	12.9		6.7	6.6	7.5	7.3	0.8	0.7	135.8	137.6	741.4	1.41	742.7	1.56	
	C	22.5	22.4	12.8		6.8	6.8	7.6	7.6	0.8	0.7	131.4	131.6	740.1	1.27	743.4	1.64	
	D	22.5	22.5	12.5		6.8	6.8	7.3	7.2	0.7	0.6	133.8	133.8	740.5	1.31	743.2	1.62	
9	A	22.6	22.5	12.4		6.8	6.8	7.3	7.6	0.6	0.7	133.8	135.6	742.2	1.49	744.3	1.75	
	B	22.5	22.5	12.6		6.8	6.7	7.5	7.3	0.9	0.7	131.9	132.6	741.4	1.40	742.5	1.53	
	C	22.4	22.5	12.6		6.8	6.8	7.6	7.8	0.8	0.9	132.6	134.8	740.1	1.27	743.4	1.64	
	D	22.5	22.5	12.5		6.8	6.8	7.3	7.8	0.8	0.6	131.8	136.5	740.5	1.31	743.2	1.61	
10	A	22.6	22.5			6.7		7.6		0.5		137.1		741.7	1.51	744.3	1.86	
	B	22.5	22.4			6.8		7.7		0.7		131.5		741.4	1.48	742.7	1.64	
	C	22.4	22.5			6.8		7.9		0.9		131.6		740.4	1.37	743.2	1.70	
	D	22.5	22.4			6.7		7.2		0.9		133.1		740.5	1.38	743.2	1.70	
	MIN	22.1	**22.3**	**12.3**	**0**	**6.7**	**6.6**	**6.9**	**7.1**	**0.4**	**0.4**	**129.7**	**131.1**	**0.0**	**0.00**	**740.9**	**1.30**	
	MAX	22.8	**22.8**	**13.1**	**0**	**6.9**	**6.9**	**7.9**	**7.9**	**0.9**	**0.9**	**138.1**	**142.8**	**742.8**	**1.58**	**744.9**	**1.88**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.8**	**6.8**	**7.5**	**7.5**	**0.7**	**0.7**	**133.6**	**136.0**	**673.7**	**1.26**	**743.3**	**1.64**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.03	0.03	0.02	0.02	0.30	0.39	32.49	0.062	0.13	0.019	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

FEL

Tier 1 Parameters

3.12 mg/L S2- 0.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.3		12.7			6.7		7.0		0.8		143.9	0.0	0.0	744.6	1.75	
	B	22.2		12.6			6.7		7.5		0.7		146.2	0.0	0.0	752.8	3.40	
	C	22.2		13.0			6.7		7.7		0.9		145.2	0.0	0.0	751.1	2.96	
	D	22.5		12.5			6.7		7.5		0.7		146.1	0.0	0.0	754.0	3.75	
1	A	22.5	22.5	13.0		6.7	6.7	8.2	7.9	0.7	0.8	142.8	145.8	748.9	2.54	752.6	3.39	
	B	22.5	22.3	13.1		6.7	6.7	7.4	7.7	0.8	0.9	142.8	145.2	749.5	2.66	751.6	3.13	
	C	22.5	22.6	12.8		6.7	6.7	7.5	7.7	0.8	0.8	142.9	143.6	748.9	2.54	752.1	3.26	
	D	22.6	22.6	12.7		6.6	6.8	7.8	7.8	0.7	0.8	144.8	146.1	749.5	2.66	753.5	3.63	
2	A	22.4	22.5	12.7		6.7	6.6	7.0	7.6	0.8	0.9	141.4	142.8	748.5	2.49	752.6	3.43	
	B	22.4	22.6	12.5		6.8	6.7	7.6	7.9	0.8	0.5	141.6	144.8	749.1	2.61	751.6	3.17	
	C	22.8	22.5	12.7		6.6	6.5	7.8	7.5	0.8	0.9	141.8	142.6	748.9	2.57	750.3	2.86	
	D	22.8	22.7	12.8		6.7	6.6	7.7	7.8	0.7	0.9	141.1	143.5	749.5	2.69	753.5	3.67	
3	A	22.6	22.5	12.6		6.7	6.6	7.8	7.7	0.9	0.6	142.7	144.8	748.5	2.48	752.4	3.36	
	B	22.7	22.6	12.5		6.7	6.6	7.4	7.7	0.6	0.5	140.7	142.7	749.4	2.66	751.6	3.16	
	C	22.5	22.6	12.7		6.8	6.7	7.3	7.6	0.9	0.8	140.8	142.8	748.9	2.56	750.5	2.90	
	D	22.5	22.6	12.8		6.7	6.7	7.5	7.5	0.9	0.7	140.1	142.8	749.1	2.60	753.5	3.66	
4	A	22.7	22.5	12.7		6.7	6.6	6.9	7.2	0.6	0.8	142.8	143.4	748.0	2.34	752.4	3.29	
	B	22.5	22.7	12.5		6.8	6.7	7.2	7.4	0.5	0.7	142.8	145.8	749.4	2.61	751.1	2.98	
	C	22.8	22.7	12.6		6.7	6.7	7.5	7.8	0.5	0.8	140.8	142.9	748.7	2.47	750.0	2.73	
	D	22.8	22.7	12.7		6.7	6.6	7.7	7.9	0.7	0.6	144.7	146.9	749.2	2.57	753.5	3.58	
5	A	22.4	22.4	12.9		6.7	6.7	7.4	7.3	0.7	0.8	142.7	144.8	748.0	2.34	752.4	3.28	
	B	22.6	22.5	12.4		6.7	6.6	7.2	7.5	0.6	0.6	142.9	143.6	749.1	2.55	751.3	3.02	
	C	22.6	22.5	12.3		6.7	6.7	7.4	7.2	0.9	0.8	142.6	144.8	748.7	2.47	750.2	2.77	
	D	22.8	22.5	12.8		6.7	6.7	7.9	7.6	0.9	0.7	142.9	150.8	749.1	2.55	753.2	3.49	
6	A	22.5	22.5	12.8		6.7	6.7	7.4	7.6	0.5	0.8	142.8	143.7	748.0	2.32	752.5	3.29	
	B	22.5	22.4	12.8		6.5	6.5	7.7	7.5	0.6	0.8	144.8	147.4	749.3	2.57	751.3	3.00	
	C	22.5	22.4	12.7		6.7	6.6	7.3	7.6	0.5	0.5	140.9	142.1	748.7	2.45	750.2	2.75	
	D	22.7	22.3	12.5		6.8	6.7	7.5	7.6	0.8	0.9	142.8	144.4	749.5	2.61	753.2	3.48	
7	A	22.5	22.4	12.7		6.7	6.6	7.4	7.5	0.9	0.5	142.8	144.5	748.0	2.33	752.5	3.29	
	B	22.5	22.5	12.8		6.6	6.5	7.3	7.5	0.8	0.7	140.2	142.9	749.3	2.57	751.4	3.02	
	C	22.5	22.5	12.8		6.7	6.7	7.4	7.3	0.6	0.7	142.8	143.7	748.7	2.46	750.2	2.76	
	D	22.5	22.4	12.6		6.9	6.8	7.3	7.7	0.6	0.8	144.9	146.7	749.5	2.61	753.5	3.56	
8	A	22.4	22.7	13.0		6.7	6.6	7.6	7.9	0.7	0.5	142.9	143.6	748.0	2.35	752.5	3.33	
	B	22.7	22.4	13.0		6.7	6.6	7.4	7.5	0.7	0.6	142.9	143.9	749.3	2.60	751.6	3.10	
	C	22.4	22.5	12.6		6.8	6.7	7.5	7.3	0.8	0.8	141.8	142.8	748.3	2.40	750.5	2.85	
	D	22.6	22.6	12.4		6.7	6.7	7.4	7.6	0.9	0.8	142.9	145.8	749.5	2.64	753.5	3.59	
9	A	22.5	22.4	12.5		6.8	6.7	7.4	7.1	0.9	0.8	142.9	143.8	748.0	2.34	752.3	3.27	
	B	22.5	22.5	12.5		6.7	6.6	7.2	7.9	0.6	0.7	140.8	143.8	749.5	2.63	751.6	3.10	
	C	22.6	22.5	12.8		6.7	6.7	7.3	7.5	0.7	0.8	141.9	143.5	748.3	2.40	750.5	2.84	
	D	22.5	22.6	12.5		6.7	6.7	7.5	7.2	0.7	0.8	142.8	143.9	749.5	2.63	753.1	3.48	
10	A	22.5	22.5			6.6		7.2		0.6		142.8		748.3	2.54	752.1	3.42	
	B	22.4	22.4			6.8		7.5		0.8		140.9		749.5	2.79	751.6	3.28	
	C	22.5	22.4			6.6		7.2		0.5		142.8		748.7	2.62	750.5	3.01	
	D	22.6	22.5			6.7		7.5		0.9		140.5		749.5	2.79	753.1	3.69	
	MIN	22.2	**22.3**	**12.3**	**0**	**6.5**	**6.5**	**6.9**	**7.0**	**0.5**	**0.5**	**140.1**	**142.1**	**0.0**	**0.00**	**744.6**	**1.75**	
	MAX	22.8	**22.7**	**13.1**	**0**	**6.9**	**6.8**	**8.2**	**7.9**	**0.9**	**0.9**	**144.9**	**150.8**	**749.5**	**2.79**	**754.0**	**3.75**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.7**	**6.7**	**7.5**	**7.6**	**0.7**	**0.7**	**142.3**	**144.5**	**680.8**	**2.31**	**751.8**	**3.20**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.04	0.04	0.02	0.02	0.20	0.27	32.83	0.113	0.24	0.055	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

FEL

Tier 1 Parameters

7.80 mg/L S2- 0.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.5		12.8			6.6		7.2		0.8		150.4	0.0	0.0	763.5	8.10	
	B	22.5		12.9			6.5		7.8		0.8		153.1	0.0	0.0	762.9	7.72	
	C	22.4		12.9			6.5		7.5		0.7		151.8	0.0	0.0	763.8	8.30	
	D	22.4		12.7			6.7		7.3		0.7		153.3	0.0	0.0	763.1	7.85	
1	A	22.4	22.5	12.8		6.6	6.5	7.5	7.3	0.6	0.7	150.9	155.5	760.1	6.07	763.4	7.86	
	B	22.4	22.5	12.9		6.6	6.5	7.6	7.8	0.7	0.8	151.7	156.5	760.3	6.17	763.9	8.17	
	C	22.4	22.5	12.9		6.5	6.6	7.9	7.7	0.9	0.7	151.6	154.5	760.2	6.12	762.5	7.32	
	D	22.6	22.5	12.5		6.6	6.7	7.7	7.9	0.9	0.7	153.9	156.8	760.4	6.22	763.1	7.67	
2	A	22.4	22.3	12.8		6.5	6.5	7.2	7.1	0.6	0.4	153.5	155.9	760.0	6.11	763.4	7.96	
	B	22.4	22.5	12.4		6.6	6.6	7.7	7.6	0.9	0.7	152.8	156.2	760.3	6.25	763.5	8.03	
	C	22.7	22.5	12.8		6.5	6.5	7.6	7.6	0.6	0.7	150.9	153.3	760.0	6.11	762.5	7.42	
	D	22.6	22.8	12.9		6.5	6.5	7.6	7.8	0.9	0.9	152.7	155.1	760.4	6.30	763.0	7.72	
3	A	22.5	22.5	12.6		6.6	6.6	7.9	7.8	0.8	0.7	151.8	153.9	763.0	7.64	763.4	7.88	
	B	22.8	22.7	12.6		6.6	6.5	7.8	7.8	0.8	0.7	151.5	153.2	760.5	6.29	763.7	8.07	
	C	22.4	22.5	12.8		6.6	6.5	7.9	7.5	0.7	0.5	151.9	153.9	760.1	6.10	762.5	7.35	
	D	22.4	22.7	12.7		6.6	6.5	7.6	7.7	0.6	0.6	150.8	153.9	760.4	6.25	763.1	7.70	
4	A	22.7	23.0	12.4		6.5	6.5	7.4	7.5	0.8	0.7	151.6	153.5	763.1	7.51	763.1	7.51	
	B	22.5	22.9	12.6		6.6	6.6	7.5	7.6	0.9	0.8	155.8	157.2	760.5	6.15	763.0	7.45	
	C	22.7	22.7	12.7		6.5	6.5	7.6	7.6	0.6	0.7	151.6	153.7	760.3	6.05	762.5	7.17	
	D	22.7	22.6	12.8		6.5	6.4	7.7	7.7	0.6	0.5	154.9	155.8	760.0	5.91	763.0	7.45	
5	A	22.5	22.5	12.7		6.6	6.5	7.2	7.6	0.6	0.7	151.6	153.1	763.1	7.49	763.4	7.66	
	B	22.5	22.4	12.5		6.5	6.5	7.6	7.0	0.7	0.8	151.8	153.5	760.3	6.04	763.2	7.55	
	C	22.5	22.3	12.7		6.6	6.5	7.7	7.8	0.7	0.8	153.9	156.2	760.1	5.94	762.5	7.15	
	D	22.9	22.6	12.9		6.6	6.5	7.5	7.4	0.8	0.6	153.9	157.2	760.0	5.90	763.3	7.61	
6	A	22.4	22.4	12.7		6.6	6.6	7.1	7.5	0.6	0.7	156.5	157.8	763.1	7.51	763.7	7.86	
	B	22.3	22.5	12.9		6.5	6.5	7.8	7.6	0.8	0.7	153.9	156.9	760.0	5.90	763.2	7.56	
	C	22.5	22.4	12.5		6.5	6.6	7.7	7.8	0.6	0.8	151.8	153.8	760.1	5.94	762.5	7.16	
	D	22.5	22.3	12.7		6.6	6.6	7.4	7.2	0.9	0.8	153.9	156.8	760.2	5.99	763.1	7.51	
7	A	22.4	22.5	12.8		6.6	6.5	7.6	7.8	0.7	0.8	151.6	154.7	763.1	7.47	763.7	7.83	
	B	22.4	22.5	12.7		6.5	6.5	7.8	7.4	0.6	0.8	151.7	154.8	760.0	5.88	763.6	7.77	
	C	22.5	22.4	12.9		6.6	6.6	7.5	7.2	0.7	0.8	151.7	152.8	760.1	5.93	762.5	7.13	
	D	22.5	22.6	12.5		6.8	6.7	7.6	7.7	0.9	0.7	152.6	155.6	760.2	5.97	763.4	7.65	
8	A	22.6	22.6	12.9		6.6	6.5	7.8	7.7	0.6	0.8	156.2	157.1	763.3	7.68	763.9	8.05	
	B	22.6	22.5	13.1		6.6	6.5	7.6	7.5	0.8	0.9	152.1	154.1	760.0	5.95	763.6	7.86	
	C	22.6	22.6	12.7		6.6	6.6	7.4	7.5	0.7	0.7	152.6	151.9	760.0	5.95	762.7	7.33	
	D	22.5	22.5	12.5		6.6	6.5	7.6	7.5	0.7	0.9	155.6	154.6	760.2	6.04	763.4	7.74	
9	A	22.4	22.6	12.6		6.6	6.6	7.7	7.5	0.6	0.5	155.4	151.5	763.1	7.59	763.9	8.08	
	B	22.4	22.4	12.5		6.5	6.5	7.6	7.3	0.8	0.8	151.5	152.7	760.0	5.96	763.6	7.89	
	C	22.5	22.4	12.6		6.6	6.6	7.7	7.8	0.6	0.7	151.6	153.7	760.3	6.10	762.3	7.13	
	D	22.6	22.5	12.6		6.6	6.5	7.7	7.6	0.9	0.8	151.7	154.8	760.5	6.20	763.4	7.77	
10	A	22.4	22.5			6.5		7.0		0.5		155.7		763.1	8.08	763.9	8.60	
	B	22.5	22.5			6.6		7.4		0.9		151.6		760.2	6.44	763.2	8.14	
	C	22.6	22.5			6.5		7.5		0.7		154.9		760.3	6.49	762.3	7.59	
	D	22.5	22.6			6.6		7.6		0.8		151.6		760.8	6.75	763.0	8.01	
	MIN	22.3	**22.3**	**12.4**	**0**	**6.5**	**6.4**	**7.0**	**7.0**	**0.5**	**0.4**	**150.8**	**150.4**	**0.0**	**0.00**	**762.3**	**7.13**	
	MAX	22.9	**23.0**	**13.1**	**0**	**6.8**	**6.7**	**7.9**	**7.9**	**0.9**	**0.9**	**156.5**	**157.8**	**763.3**	**8.08**	**763.9**	**8.60**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.6**	**6.5**	**7.6**	**7.6**	**0.7**	**0.7**	**152.8**	**154.5**	**691.6**	**5.83**	**763.2**	**7.71**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.03	0.04	0.02	0.02	0.26	0.28	33.35	0.296	0.07	0.051	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters

HS-1 (1:4) 2.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.4		12.9			7.1		7.3		0.5		55.8	0.0	0.0	0.0	0.0	
	B	22.4		13.2			7.0		7.4		0.6		55.2	0.0	0.0	0.0	0.0	
	C	22.5		12.8			7.0		7.8		0.6		56.3	0.0	0.0	0.0	0.0	
	D	22.4		12.9			6.6		7.4		0.5		55.5	0.0	0.0	0.0	0.0	
1	A	22.3	22.3	12.9		7.0	7.0	7.6	7.5	0.5	0.8	55.3	56.1	0.0	0.0	0.0	0.0	
	B	22.3	22.4	12.8		7.1	7.0	7.4	7.5	0.9	0.8	54.2	57.3	0.0	0.0	0.0	0.0	
	C	22.3	22.4	12.7		7.1	7.0	7.8	7.5	0.7	0.8	53.6	54.2	0.0	0.0	0.0	0.0	
	D	22.7	22.5	12.9		7.0	7.0	7.8	7.9	0.8	0.8	54.1	54.7	0.0	0.0	0.0	0.0	
2	A	22.4	22.4	12.7		7.0	7.0	7.3	7.0	0.8	0.3	55.1	56.1	0.0	0.0	0.0	0.0	
	B	22.4	22.4	12.5		7.0	7.0	7.3	7.4	0.8	0.8	52.8	53.9	0.0	0.0	0.0	0.0	
	C	22.5	22.5	12.9		7.1	7.0	7.5	7.7	0.8	0.5	55.3	57.2	0.0	0.0	0.0	0.0	
	D	22.7	22.7	12.8		7.0	6.9	7.9	7.8	0.8	0.7	56.5	57.2	0.0	0.0	0.0	0.0	
3	A	22.6	22.6	12.5		7.1	7.0	7.5	7.6	0.9	0.8	55.2	57.2	0.0	0.0	0.0	0.0	
	B	22.7	22.6	12.7		7.0	6.9	7.9	7.7	0.7	0.9	54.1	56.8	0.0	0.0	0.0	0.0	
	C	22.6	22.7	12.8		7.0	6.9	7.7	7.4	0.8	0.7	55.2	57.4	0.0	0.0	0.0	0.0	
	D	22.6	22.5	12.6		7.0	6.9	7.8	7.5	0.8	0.9	53.7	55.5	0.0	0.0	0.0	0.0	
4	A	22.6	23.1	12.5		7.0	6.9	7.6	7.6	0.6	0.5	55.9	56.8	0.0	0.0	0.0	0.0	
	B	22.5	22.9	12.9		7.1	7.0	7.8	7.5	0.8	0.8	54.1	56.9	0.0	0.0	0.0	0.0	
	C	22.5	22.5	12.8		7.0	6.9	7.7	7.8	0.7	0.9	53.9	54.1	0.0	0.0	0.0	0.0	
	D	22.5	22.4	12.7		7.1	7.0	7.8	7.5	0.8	0.8	54.8	56.2	0.0	0.0	0.0	0.0	
5	A	22.4	22.5	12.6		7.0	6.9	7.3	7.5	0.7	0.8	52.6	55.6	0.0	0.0	0.0	0.0	
	B	22.4	22.5	12.4		7.1	6.9	7.4	7.3	0.6	0.8	52.9	53.7	0.0	0.0	0.0	0.0	
	C	22.7	22.5	12.8		7.0	6.9	7.9	7.7	0.9	0.7	53.8	54.8	0.0	0.0	0.0	0.0	
	D	22.8	22.5	13.0		7.1	7.0	7.2	7.5	0.7	0.8	55.8	56.1	0.0	0.0	0.0	0.0	
6	A	22.5	22.5	12.5		7.0	6.9	7.8	7.5	0.8	0.7	53.7	54.9	0.0	0.0	0.0	0.0	
	B	22.5	22.4	13.1		7.0	6.9	7.3	7.4	0.9	0.9	53.6	54.2	0.0	0.0	0.0	0.0	
	C	22.4	22.5	12.6		7.1	7.0	7.5	7.1	0.9	0.8	54.1	56.3	0.0	0.0	0.0	0.0	
	D	22.6	22.4	13.0		7.1	7.0	7.0	7.3	0.7	0.6	54.6	57.3	0.0	0.0	0.0	0.0	
7	A	22.5	22.6	12.7		7.0	6.9	7.8	7.7	0.9	0.7	52.6	53.8	0.0	0.0	0.0	0.0	
	B	22.5	22.4	12.9		7.1	7.0	7.2	7.5	0.9	0.7	54.1	56.2	0.0	0.0	0.0	0.0	
	C	22.6	22.5	12.7		7.0	6.9	7.6	7.5	0.9	0.8	53.6	54.6	0.0	0.0	0.0	0.0	
	D	22.5	22.5	12.8		7.1	6.9	7.8	7.6	0.7	0.8	53.5	54.8	0.0	0.0	0.0	0.0	
8	A	22.7	22.9	13.1		7.0	6.9	7.7	7.5	0.5	0.5	53.7	54.2	0.0	0.0	0.0	0.0	
	B	22.8	22.6	12.6		7.1	7.0	7.4	7.3	0.7	0.8	53.8	54.6	0.0	0.0	0.0	0.0	
	C	22.5	22.5	12.8		6.9	6.8	7.6	7.6	0.6	0.7	54.3	54.2	0.0	0.0	0.0	0.0	
	D	22.5	22.5	12.6		7.0	7.0	7.7	7.6	0.8	0.8	55.1	53.8	0.0	0.0	0.0	0.0	
9	A	22.6	22.5	12.5		7.0	6.9	7.8	7.3	0.8	0.7	52.3	53.7	0.0	0.0	0.0	0.0	
	B	22.6	22.5	12.4		7.0	6.9	7.5	7.1	0.9	0.7	54.7	55.6	0.0	0.0	0.0	0.0	
	C	22.4	22.5	12.6		7.0	6.9	7.5	7.2	0.5	0.8	54.1	55.1	0.0	0.0	0.0	0.0	
	D	22.6	22.5	12.5		7.0	6.9	7.6	7.3	0.6	0.6	54.5	56.2	0.0	0.0	0.0	0.0	
10	A	22.5	22.4			7.0		6.8		0.9		53.6		0.0	0.0	0.0	0.0	
	B	22.5	22.4			7.0		7.6		0.8		54.5		0.0	0.0	0.0	0.0	
	C	22.5	22.6			7.1		7.1		0.8		53.6		0.0	0.0	0.0	0.0	
	D	22.4	22.5			7.0		7.0		0.6		53.6		0.0	0.0	0.0	0.0	
	MIN	22.3	22.3	12.4	0	6.9	6.6	6.8	7.0	0.5	0.3	52.3	53.7	0.0	0.00	0.0	0.00	
	MAX	22.8	23.1	13.2	0	7.1	7.1	7.9	7.9	0.9	0.9	56.5	57.4	0.0	0.00	0.0	0.00	
	MEAN	22.5	22.5	12.7	N/A	7.0	6.9	7.5	7.5	0.8	0.7	54.2	55.5	0.0	0.00	0.0	0.00	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.04	0.03	0.02	0.02	0.15	0.19	0.00	0.000	0.00	0.000	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters

0.3 mg/L S2- 2.8 mg/L Fe

IMAM01-00420

								Headspace DO		Aquatic DO				Sulfide,		Sulfide,		
Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	Pre-Renew ORP	Post-Renew ORP	mV Reading (mV)	Calc Conc (mg/L)	mV Reading (mV)	Calc Conc (mg/L)	Comments/Observations
0	A	22.3		13.1			6.9		7.4		0.5		127.9	0.0	0.0	723.5	0.32	
	B	22.3		13.0			6.9		7.5		0.8		133.5	0.0	0.0	724.3	0.34	
	C	22.4		12.7			6.9		7.9		0.8		136.3	0.0	0.0	724.8	0.35	
	D	22.5		12.8			6.9		7.5		0.6		131.5	0.0	0.0	723.3	0.31	
1	A	22.4	22.4	13.1		6.8	6.8	7.9	7.8	0.5	0.6	127.1	129.9	717.2	0.21	723.1	0.34	
	B	22.4	22.5	12.7		6.9	6.8	7.9	7.8	0.8	0.7	127.4	130.3	718.4	0.24	725.2	0.40	
	C	22.6	22.5	12.8		6.8	6.9	7.6	7.6	0.9	0.8	128.1	130.9	717.3	0.22	723.8	0.36	
	D	22.5	22.6	12.8		6.9	6.8	7.7	7.6	0.8	0.9	126.8	128.3	718.5	0.24	724.1	0.37	
2	A	22.5	22.3	12.5		6.9	6.8	7.5	7.4	0.7	0.5	124.9	128.6	717.0	0.21	723.2	0.34	
	B	22.5	22.5	12.4		6.9	6.8	7.9	7.2	0.9	0.7	128.3	129.1	718.4	0.24	725.2	0.40	
	C	22.6	22.6	12.8		6.9	6.8	7.8	7.6	0.8	0.9	126.7	134.7	717.1	0.21	723.5	0.35	
	D	22.5	22.8	12.9		6.9	6.8	7.5	7.6	0.7	0.6	126.9	128.1	718.5	0.24	724.3	0.38	
3	A	22.6	22.6	12.8		6.9	6.8	7.8	7.8	0.7	0.7	127.1	130.5	717.2	0.22	723.4	0.35	
	B	22.5	22.5	12.9		6.9	6.9	7.5	7.6	0.8	0.6	127.2	128.9	718.4	0.24	725.2	0.41	
	C	22.7	22.8	12.9		6.9	6.8	7.6	7.2	0.9	0.5	121.7	123.8	717.1	0.22	723.1	0.35	
	D	22.7	22.5	12.5		6.9	6.8	7.9	7.7	0.9	0.8	126.3	127.1	718.3	0.24	724.3	0.38	
4	A	22.7	22.8	12.6		6.9	6.8	7.7	7.8	0.9	0.8	127.1	129.5	717.0	0.21	723.1	0.34	
	B	22.6	23.0	13.0		6.9	6.8	7.6	7.9	0.6	0.7	127.1	128.4	718.4	0.24	725.2	0.40	
	C	22.8	22.6	12.9		6.9	6.8	7.5	7.6	0.6	0.7	129.3	130.5	717.1	0.22	723.2	0.35	
	D	22.8	22.7	13.0		6.9	6.8	7.9	7.6	0.9	0.8	126.9	127.4	718.4	0.24	724.3	0.38	
5	A	22.6	22.4	12.9		6.9	6.8	7.5	7.4	0.8	0.9	127.2	130.4	717.1	0.22	723.1	0.34	
	B	22.5	22.6	12.6		6.9	6.8	7.5	7.2	0.5	0.9	127.1	129.2	718.4	0.24	725.7	0.42	
	C	22.5	23.0	12.9		6.8	6.7	7.8	7.6	0.8	0.8	126.9	130.9	717.3	0.22	723.1	0.34	
	D	22.7	22.4	12.8		6.9	6.8	7.0	7.3	0.8	0.6	126.8	128.1	718.4	0.24	724.3	0.38	
6	A	22.4	22.4	12.9		6.9	6.8	7.7	7.9	0.7	0.8	126.1	128.6	717.3	0.21	723.4	0.34	
	B	22.6	22.5	12.7		6.9	6.9	7.7	7.6	0.8	0.8	121.9	122.8	718.4	0.23	725.7	0.41	
	C	22.6	22.6	12.5		6.9	6.8	7.6	7.7	0.7	0.6	126.9	127.1	717.5	0.22	723.6	0.35	
	D	22.6	22.3	12.9		6.9	6.9	6.9	7.2	0.6	0.8	121.6	124.8	718.4	0.23	724.3	0.37	
7	A	22.4	22.5	12.8		6.9	6.8	7.5	7.4	0.6	0.5	127.1	127.1	717.3	0.22	723.1	0.34	
	B	22.4	22.5	12.7		6.9	6.8	7.3	7.6	0.5	0.7	127.1	131.5	718.4	0.24	725.7	0.42	
	C	22.5	22.6	12.8		6.9	6.8	7.3	7.3	0.7	0.5	128.5	130.9	717.5	0.22	723.2	0.34	
	D	22.6	22.5	12.7		6.9	6.8	7.9	7.7	0.5	0.7	127.1	129.1	718.4	0.24	724.3	0.37	
8	A	22.8	22.8	12.8		6.8	6.7	7.8	7.7	0.6	0.7	125.9	127.1	717.1	0.21	723.5	0.35	
	B	22.7	22.5	12.9		6.8	6.9	7.2	7.3	0.6	0.7	125.2	126.1	718.4	0.24	725.7	0.42	
	C	22.5	22.5	12.9		6.8	6.7	7.5	7.5	0.8	0.7	130.9	125.2	717.5	0.22	723.4	0.35	
	D	22.5	22.5	12.6		6.9	6.8	7.5	7.7	0.9	0.8	122.8	125.2	718.1	0.23	724.3	0.37	
9	A	22.5	22.5	12.5		6.9	6.9	7.5	7.4	0.6	0.8	126.1	128.1	717.4	0.22	723.5	0.35	
	B	22.5	22.4	12.5		6.9	6.8	7.0	6.8	0.8	0.8	127.2	130.6	718.4	0.23	725.2	0.40	
	C	22.3	22.4	12.5		6.9	6.9	7.7	7.8	0.6	0.7	128.1	131.1	717.6	0.22	723.4	0.34	
	D	22.5	22.4	12.5		6.9	6.9	7.8	7.6	0.7	0.8	123.7	128.5	718.2	0.23	724.3	0.37	
10	A	22.5	22.4			6.9		7.3		0.8		128.6		717.6	0.23	723.5	0.36	
	B	22.4	22.4			6.9		7.7		0.7		126.8		718.5	0.25	725.6	0.43	
	C	22.5	22.5			6.8		7.6		0.9		126.9		717.6	0.23	723.4	0.36	
	D	22.5	22.5			6.9		7.3		0.7		124.5		718.2	0.24	724.3	0.39	
	MIN	22.3	**22.3**	**12.4**	**0**	**6.8**	**6.7**	**6.9**	**6.8**	**0.5**	**0.5**	**121.6**	**122.8**	**0.0**	**0.00**	**723.1**	**0.31**	
	MAX	22.8	**23.0**	**13.1**	**0**	**6.9**	**6.9**	**7.9**	**7.9**	**0.9**	**0.9**	**130.9**	**136.3**	**718.5**	**0.25**	**725.7**	**0.43**	
	MEAN	22.5	**22.5**	**12.8**	**N/A**	**6.9**	**6.8**	**7.6**	**7.5**	**0.7**	**0.7**	**126.5**	**128.9**	**652.6**	**0.21**	**724.1**	**0.37**	
	SEM	0.02	0.03	0.03	N/A	0.01	0.01	0.04	0.04	0.02	0.02	0.31	0.43	31.47	0.010	0.13	0.004	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters

1.56 mg/L S2- 2.8 mg/L Fe

IMAM01-00420

								Headspace DO		Aquatic DO				Sulfide,		Sulfide,		
Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Pre-Renew	Post-Renew	Pre-Renew	Post-Renew	Pre-Renew ORP	Post-Renew ORP	mV Reading (mV)	Calc Conc (mg/L)	mV Reading (mV)	Calc Conc (mg/L)	Comments/Observations
0	A	22.4		12.7			6.8		7.2		0.7		134.6	0.0	0.0	745.0	1.81	
	B	22.4		12.7			6.8		7.5		0.9		140.6	0.0	0.0	743.9	1.65	
	C	22.4		12.6			6.8		7.8		0.9		140.8	0.0	0.0	742.5	1.48	
	D	22.3		12.9			6.8		7.8		0.8		140.8	0.0	0.0	743.1	1.55	
1	A	22.3	22.3	13.0		6.7	6.7	7.3	7.5	0.7	0.8	135.9	138.3	738.5	1.13	744.0	1.73	
	B	22.3	22.3	12.9		6.8	6.7	7.6	7.5	0.7	0.6	136.1	140.7	738.0	1.08	742.6	1.55	
	C	22.5	22.6	12.8		6.8	6.8	7.8	7.7	0.7	0.8	134.9	137.1	737.2	1.02	743.5	1.67	
	D	22.4	22.5	12.8		6.8	6.7	7.8	7.9	0.7	0.8	137.2	142.9	737.0	1.00	743.1	1.61	
2	A	22.4	22.3	12.5		6.8	6.8	7.4	7.4	0.8	0.9	131.5	133.8	738.2	1.11	744.2	1.78	
	B	22.4	22.5	12.5		6.8	6.8	7.7	7.3	0.6	0.5	135.6	137.4	738.0	1.09	742.3	1.53	
	C	22.4	22.5	12.7		6.8	6.8	7.3	7.5	0.6	0.7	135.8	137.5	737.3	1.04	743.5	1.68	
	D	22.6	22.7	13.0		6.8	6.7	7.8	7.9	0.8	0.9	133.1	135.2	737.0	1.01	743.3	1.66	
3	A	22.5	22.4	12.7		6.8	6.7	7.7	7.6	0.8	0.6	131.3	134.7	738.2	1.12	744.2	1.78	
	B	22.6	22.5	12.8		6.8	6.7	7.8	7.7	0.7	0.9	133.5	135.7	738.0	1.10	742.3	1.54	
	C	22.5	22.6	12.8		6.8	6.8	7.8	7.6	0.8	0.8	133.3	135.3	737.5	1.06	743.2	1.65	
	D	22.5	22.7	12.4		6.9	6.8	7.6	7.6	0.7	0.7	135.8	140.8	737.0	1.02	743.3	1.66	
4	A	22.5	22.9	12.8		6.8	6.7	7.5	7.3	0.7	0.5	133.8	135.7	738.0	1.08	744.2	1.75	
	B	22.7	22.8	12.8		6.8	6.7	7.5	7.3	0.6	0.9	132.6	135.9	738.2	1.10	742.5	1.53	
	C	22.9	22.8	12.6		6.8	6.7	7.4	7.7	0.5	0.8	135.8	137.2	737.5	1.04	743.2	1.62	
	D	22.9	22.8	12.6		6.7	6.6	7.5	7.8	0.7	0.6	133.5	135.8	737.3	1.03	743.3	1.63	
5	A	22.7	22.5	12.7		6.9	6.7	7.4	7.2	0.7	0.8	133.9	140.2	738.4	1.12	744.5	1.79	
	B	22.6	22.4	12.5		6.8	6.7	7.3	7.0	0.7	0.8	130.4	133.9	738.2	1.10	742.5	1.53	
	C	22.6	22.8	13.0		6.7	6.6	7.5	7.7	0.7	0.6	133.8	136.1	737.5	1.04	743.1	1.60	
	D	22.5	22.5	12.7		6.8	6.7	7.7	7.5	0.7	0.7	135.8	138.2	737.1	1.01	743.3	1.63	
6	A	22.4	22.5	13.0		6.7	6.7	7.6	7.5	0.9	0.8	133.0	135.2	738.6	1.12	744.1	1.71	
	B	22.5	22.5	12.8		6.8	6.8	7.8	7.5	0.7	0.7	130.8	132.7	738.4	1.10	742.5	1.51	
	C	22.5	22.5	12.5		6.8	6.8	7.5	7.6	0.8	0.7	133.8	135.8	737.5	1.03	743.1	1.58	
	D	22.5	22.4	12.8		6.7	6.7	7.1	7.4	0.8	0.8	130.7	132.9	737.3	1.01	743.5	1.63	
7	A	22.5	22.4	12.7		6.8	6.7	7.6	7.5	0.8	0.9	134.6	135.6	738.6	1.12	744.4	1.76	
	B	22.5	22.5	12.8		6.8	6.7	7.5	7.8	0.6	0.8	133.3	136.1	738.4	1.11	742.5	1.52	
	C	22.6	22.5	12.9		6.8	6.7	7.2	7.8	0.6	0.4	131.1	140.0	737.5	1.03	743.1	1.59	
	D	22.5	22.6	12.9		6.8	6.8	7.2	7.6	0.6	0.8	135.9	137.4	737.3	1.02	743.1	1.59	
8	A	22.6	22.7	12.7		6.9	6.8	7.6	7.6	0.7	0.8	134.8	135.8	738.6	1.13	744.4	1.77	
	B	22.7	22.5	12.8		6.8	6.8	7.5	7.4	0.5	0.6	133.9	135.9	738.4	1.11	742.7	1.56	
	C	22.5	22.4	13.1		6.7	6.6	7.4	7.6	0.9	0.8	136.5	131.6	737.2	1.02	743.1	1.60	
	D	22.6	22.6	12.8		6.8	6.7	7.5	7.4	0.7	0.7	134.9	136.8	737.3	1.02	743.5	1.66	
9	A	22.5	22.5	12.4		6.8	6.8	7.6	7.7	0.8	0.7	131.8	134.6	738.6	1.13	744.4	1.77	
	B	22.5	22.5	12.5		6.7	6.7	7.3	7.5	0.6	0.8	131.5	132.9	738.7	1.13	742.2	1.49	
	C	22.5	22.5	12.6		6.7	6.7	7.6	7.8	0.8	0.6	132.5	137.5	737.2	1.01	743.1	1.60	
	D	22.5	22.5	12.5		6.7	6.7	7.5	7.4	0.9	0.7	131.6	134.7	737.5	1.03	743.5	1.65	
10	A	22.6	22.5			6.8		7.5		0.7		133.9		738.6	1.19	744.4	1.87	
	B	22.5	22.5			6.7		7.8		0.6		133.9		738.7	1.20	742.2	1.57	
	C	22.4	22.4			6.8		7.3		0.8		132.7		737.5	1.09	743.5	1.74	
	D	22.6	22.5			6.8		7.5		0.5		131.6		737.5	1.09	743.5	1.74	
	MIN	22.3	**22.3**	**12.4**	**0**	**6.7**	**6.6**	**7.1**	**7.0**	**0.5**	**0.4**	**130.4**	**131.6**	**0.0**	**0.00**	**742.2**	**1.48**	
	MAX	22.9	**22.9**	**13.1**	**0**	**6.9**	**6.8**	**7.8**	**7.9**	**0.9**	**0.9**	**137.2**	**142.9**	**738.7**	**1.20**	**745.0**	**1.87**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.8**	**6.7**	**7.5**	**7.6**	**0.7**	**0.7**	**133.7**	**136.6**	**670.8**	**0.98**	**743.4**	**1.64**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.03	0.03	0.02	0.02	0.29	0.41	32.35	0.048	0.11	0.015	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters

3.12 mg/L S2- 2.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.5		12.5			6.7		7.3		0.8		144.1	0.0	0.0	752.6	3.35	
	B	22.5		12.5			6.6		7.6		0.5		147.2	0.0	0.0	751.2	2.99	
	C	22.5		12.8			6.8		7.6		0.9		147.4	0.0	0.0	752.5	3.32	
	D	22.4		12.6			6.7		7.6		0.9		148.5	0.0	0.0	753.0	3.46	
1	A	22.4	22.5	12.7		6.6	6.5	7.6	7.7	0.6	0.7	143.2	147.2	742.1	1.49	752.0	3.23	
	B	22.4	22.4	12.6		6.7	6.6	7.7	7.4	0.9	0.8	143.8	149.9	743.0	1.60	751.4	3.08	
	C	22.4	22.5	12.9		6.6	6.7	7.8	7.9	0.9	0.9	144.8	146.2	740.6	1.33	752.0	3.23	
	D	22.5	22.5	12.7		6.7	6.6	7.7	7.6	0.7	0.9	144.5	150.5	742.2	1.50	753.0	3.49	
2	A	22.4	22.4	12.6		6.7	6.7	7.3	7.5	0.6	0.8	140.8	142.9	742.1	1.51	752.0	3.27	
	B	22.4	22.4	12.6		6.7	6.7	7.8	7.1	0.7	0.8	143.9	145.6	743.1	1.63	751.4	3.12	
	C	22.6	22.6	12.7		6.7	6.6	7.6	7.7	0.5	0.8	142.7	144.8	740.6	1.34	752.0	3.27	
	D	22.7	22.6	12.7		6.7	6.7	7.5	7.6	0.7	0.8	142.8	143.1	742.5	1.56	753.3	3.62	
3	A	22.5	22.4	12.9		6.6	6.6	7.8	7.6	0.9	0.8	141.8	143.9	742.1	1.51	752.3	3.33	
	B	22.7	22.6	12.8		6.6	6.6	7.8	7.7	0.8	0.8	140.9	142.1	743.6	1.70	751.4	3.11	
	C	22.5	22.7	12.9		6.7	6.6	7.5	7.4	0.7	0.7	141.8	144.4	740.6	1.35	752.3	3.33	
	D	22.5	22.6	12.6		6.7	6.7	7.8	7.9	0.5	0.6	141.6	143.9	742.7	1.58	753.3	3.60	
4	A	22.6	22.7	12.6		6.6	6.5	7.7	7.1	0.8	0.8	142.4	144.8	742.4	1.52	752.5	3.32	
	B	22.6	22.9	13.1		6.7	6.7	7.2	7.0	0.8	0.7	140.8	142.8	743.6	1.67	751.4	3.05	
	C	22.4	22.5	13.0		6.8	6.7	7.8	7.7	0.6	0.9	142.6	144.7	740.2	1.28	752.3	3.26	
	D	22.4	22.5	12.8		6.6	6.5	7.4	7.3	0.8	0.5	144.7	146.9	742.7	1.56	753.5	3.58	
5	A	22.8	22.3	12.6		6.7	6.6	7.3	7.6	0.6	0.7	146.1	150.8	742.4	1.52	752.5	3.31	
	B	22.5	22.6	12.3		6.6	6.6	7.5	7.7	0.6	0.7	138.1	140.6	743.6	1.67	751.6	3.09	
	C	22.5	23.1	12.8		6.6	6.5	7.6	7.5	0.5	0.6	145.2	150.9	740.5	1.31	752.3	3.26	
	D	22.9	22.6	12.8		6.7	6.6	7.8	7.6	0.8	0.9	142.9	144.9	742.7	1.56	753.7	3.63	
6	A	22.5	22.5	12.9		6.7	6.6	7.4	7.6	0.7	0.9	142.7	144.8	742.4	1.50	752.5	3.29	
	B	22.5	22.4	12.9		6.7	6.6	7.6	7.5	0.8	0.7	141.2	144.8	743.2	1.60	751.6	3.07	
	C	22.5	22.4	12.5		6.7	6.7	7.7	7.8	0.9	0.8	142.7	146.9	740.2	1.26	752.3	3.24	
	D	22.5	22.5	12.8		6.6	6.5	7.5	7.7	0.7	0.7	142.8	145.8	742.7	1.54	753.7	3.61	
7	A	22.6	22.5	12.8		6.7	6.7	7.7	7.6	0.7	0.6	140.8	143.2	742.4	1.51	752.5	3.29	
	B	22.5	22.5	12.6		6.6	6.6	7.6	7.8	0.9	0.9	144.8	145.9	743.2	1.61	751.3	3.00	
	C	22.5	22.4	13.1		6.6	6.5	7.6	7.5	0.8	0.8	142.9	144.8	740.2	1.27	752.3	3.24	
	D	22.4	22.5	12.6		6.8	6.7	7.8	7.5	0.9	0.5	143.8	144.6	742.7	1.54	753.2	3.48	
8	A	22.7	22.6	12.6		6.7	6.6	7.7	7.8	0.9	0.6	144.6	145.7	742.4	1.52	752.5	3.33	
	B	22.6	22.7	12.7		6.7	6.7	7.6	7.7	0.8	0.9	141.8	143.6	743.5	1.66	751.5	3.08	
	C	22.5	22.5	13.0		6.7	6.6	7.5	7.5	0.8	0.6	141.8	143.5	740.2	1.28	752.3	3.27	
	D	22.5	22.5	12.7		6.7	6.6	7.6	7.5	0.8	0.9	143.5	144.8	742.7	1.56	753.2	3.51	
9	A	22.4	22.5	12.5		6.7	6.8	7.8	7.2	0.9	0.8	140.7	142.8	742.4	1.51	752.1	3.22	
	B	22.6	22.5	12.4		6.6	6.6	7.2	7.5	0.9	0.7	140.8	142.6	743.5	1.65	751.5	3.07	
	C	22.5	22.4	12.5		6.6	6.6	7.5	7.4	0.5	0.8	141.9	143.8	740.1	1.27	752.3	3.27	
	D	22.5	22.4	12.5		6.7	6.6	7.3	7.2	0.6	0.9	142.7	144.1	742.7	1.55	753.2	3.51	
10	A	22.5	22.4			6.7		7.4		0.7		142.8		742.1	1.56	752.7	3.58	
	B	22.4	22.5			6.7		7.7		0.5		141.8		743.5	1.74	751.5	3.26	
	C	22.5	22.4			6.7		7.9		0.6		143.5		740.0	1.33	752.3	3.47	
	D	22.5	22.6			6.7		7.4		0.8		142.9		742.7	1.64	753.2	3.72	
	MIN	22.4	**22.3**	**12.3**	**0**	**6.6**	**6.5**	**7.2**	**7.0**	**0.5**	**0.5**	**138.1**	**140.6**	**0.0**	**0.00**	**751.2**	**2.99**	
	MAX	22.9	**23.1**	**13.1**	**0**	**6.8**	**6.8**	**7.9**	**7.9**	**0.9**	**0.9**	**146.1**	**150.9**	**743.6**	**1.74**	**753.7**	**3.72**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.7**	**6.6**	**7.6**	**7.5**	**0.7**	**0.8**	**142.6**	**145.2**	**674.7**	**1.37**	**752.3**	**3.31**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.03	0.03	0.02	0.02	0.25	0.38	32.54	0.069	0.10	0.029	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

Tier 1 Parameters

7.80 mg/L S2- 2.8 mg/L Fe

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.3		12.8			6.5		7.4		0.8		150.8	0.0	0.0	763.3	7.97	
	B	22.3		12.8			6.5		7.6		0.6		154.5	0.0	0.0	763.9	8.37	
	C	22.3		12.7			6.6		7.5		0.8		155.8	0.0	0.0	762.2	7.29	
	D	22.5		12.5			6.6		7.7		0.8		155.5	0.0	0.0	762.4	7.41	
1	A	22.2	22.4	12.9		6.5	6.5	7.8	7.9	0.8	0.8	151.4	158.2	755.1	4.11	763.2	7.73	
	B	22.2	22.4	12.5		6.5	6.6	7.5	7.7	0.8	0.8	156.9	158.2	754.4	3.89	763.9	8.17	
	C	22.5	22.5	12.8		6.5	6.6	7.7	7.8	0.8	0.7	151.1	156.3	756.3	4.52	762.0	7.04	
	D	22.6	22.6	12.8		6.6	6.7	7.8	7.9	0.8	0.7	155.5	157.4	755.1	4.11	762.4	7.27	
2	A	22.4	22.3	12.6		6.6	6.5	6.9	7.7	0.9	0.6	152.9	155.8	755.1	4.16	763.5	8.03	
	B	22.4	22.5	12.5		6.5	6.6	7.5	7.5	0.9	0.7	154.8	155.5	754.1	3.85	763.6	8.09	
	C	22.5	22.7	12.6		6.6	6.5	7.8	7.4	0.7	0.9	150.8	152.6	756.3	4.57	762.0	7.14	
	D	22.5	22.8	12.8		6.6	6.5	7.7	7.7	0.9	0.6	154.3	156.3	755.0	4.13	762.3	7.31	
3	A	22.5	22.5	13.0		6.5	6.4	7.9	7.7	0.7	0.5	152.9	154.2	755.1	4.14	763.7	8.07	
	B	22.6	22.4	13.0		6.6	6.5	7.9	7.8	0.9	0.7	152.6	153.5	754.0	3.80	763.6	8.00	
	C	22.7	22.8	12.7		6.5	6.5	7.9	7.6	0.9	0.8	150.9	152.6	756.3	4.55	762.4	7.29	
	D	22.7	22.8	12.6		6.6	6.6	7.5	7.6	0.7	0.8	152.6	154.9	755.4	4.24	762.1	7.19	
4	A	22.6	22.8	12.5		6.5	6.4	7.4	7.5	0.9	0.8	151.5	153.6	755.2	4.08	763.2	7.57	
	B	22.6	22.9	12.7		6.6	6.5	7.4	7.3	0.5	0.6	151.7	153.1	754.0	3.72	763.2	7.57	
	C	22.6	22.5	12.8		6.6	6.5	7.9	7.7	0.8	0.8	153.4	155.2	756.1	4.38	762.4	7.12	
	D	22.6	22.6	12.9		6.5	6.5	7.5	7.6	0.7	0.7	151.6	153.8	755.1	4.05	762.0	6.90	
5	A	22.9	22.2	12.3		6.6	6.5	7.7	7.8	0.5	0.8	155.8	156.9	755.3	4.11	763.4	7.66	
	B	22.4	22.4	12.4		6.5	6.5	7.4	7.3	0.5	0.8	150.0	153.5	754.0	3.71	763.2	7.55	
	C	22.6	22.4	12.6		6.5	6.4	7.3	7.2	0.7	0.8	155.8	157.2	756.4	4.47	762.2	6.99	
	D	22.7	22.5	12.9		6.5	6.4	7.5	7.3	0.7	0.8	154.8	156.3	755.1	4.04	762.2	6.99	
6	A	22.5	22.5	12.8		6.6	6.6	7.5	7.8	0.8	0.8	151.9	153.7	755.3	4.09	763.5	7.74	
	B	22.4	22.5	12.5		6.6	6.5	7.8	7.3	0.9	0.6	153.5	154.1	754.2	3.76	763.2	7.56	
	C	22.4	22.5	12.6		6.6	6.5	7.7	7.5	0.7	0.7	154.9	156.2	756.2	4.39	762.5	7.16	
	D	22.4	22.3	12.7		6.5	6.5	7.8	7.8	0.7	0.6	151.1	153.3	755.3	4.09	762.2	7.00	
7	A	22.5	22.4	12.9		6.6	6.5	7.8	7.7	0.8	0.9	153.9	156.8	755.3	4.09	763.5	7.71	
	B	22.5	22.6	12.7		6.5	6.5	7.5	7.3	0.8	0.7	152.9	153.1	754.2	3.76	763.4	7.65	
	C	22.4	22.5	13.0		6.5	6.5	7.4	7.3	0.7	0.5	153.5	157.2	756.2	4.38	762.5	7.13	
	D	22.5	22.4	12.8		6.7	6.6	7.1	7.3	0.9	0.9	155.9	156.5	755.3	4.09	762.0	6.86	
8	A	22.9	22.5	12.5		6.6	6.5	7.6	7.7	0.7	0.8	152.9	153.8	755.1	4.07	763.7	7.92	
	B	22.8	22.5	12.5		6.5	6.5	7.3	7.5	0.7	0.6	154.6	156.9	754.2	3.79	763.4	7.74	
	C	22.6	22.5	12.8		6.6	6.5	7.3	7.2	0.7	0.7	154.9	151.9	756.4	4.50	762.7	7.33	
	D	22.4	22.6	12.5		6.6	6.5	7.4	7.6	0.7	0.8	151.6	151.7	755.3	4.13	762.2	7.05	
9	A	22.6	22.4	12.5		6.6	6.7	7.9	7.5	0.7	0.8	152.8	153.7	755.1	4.07	763.2	7.65	
	B	22.5	22.4	12.4		6.5	6.5	7.6	7.8	0.8	0.6	151.4	153.5	754.5	3.88	763.4	7.77	
	C	22.6	22.4	12.4		6.5	6.5	7.6	7.3	0.9	0.9	155.6	156.9	756.6	4.57	762.7	7.35	
	D	22.4	22.5	12.6		6.6	6.5	7.2	7.4	0.8	0.7	155.3	157.5	755.4	4.17	762.0	6.96	
10	A	22.5	22.5			6.6		7.6		0.8		156.5		755.1	4.32	763.4	8.27	
	B	22.5	22.4			6.6		7.8		0.8		151.7		754.5	4.12	763.4	8.27	
	C	22.5	22.5			6.6		7.4		0.7		154.1		756.1	4.67	762.5	7.71	
	D	22.4	22.5			6.6		7.8		0.7		153.7		755.1	4.32	762.3	7.59	
	MIN	22.2	**22.2**	**12.3**	**0**	**6.5**	**6.4**	**6.9**	**7.2**	**0.5**	**0.5**	**150.0**	**150.8**	**0.0**	**0.00**	**762.0**	**6.86**	
	MAX	22.9	**22.9**	**13.0**	**0**	**6.7**	**6.7**	**7.9**	**7.9**	**0.9**	**0.9**	**156.9**	**158.2**	**756.6**	**4.67**	**763.9**	**8.37**	
	MEAN	22.5	**22.5**	**12.7**	**N/A**	**6.6**	**6.5**	**7.6**	**7.6**	**0.8**	**0.7**	**153.4**	**155.0**	**686.6**	**3.77**	**762.9**	**7.53**	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.04	0.03	0.02	0.02	0.29	0.30	33.11	0.186	0.09	0.063	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

FEL

Tier 1 Parameters

100 mg/L BA

IMAM01-00420

Study Day	Rep	Water Bath (C)	AM Temp (C)	PM Temp (C)	Light Intensity (lux)	Pre-Renew pH	Post-Renew pH	Headspace DO Pre-Renew	Headspace DO Post-Renew	Aquatic DO Pre-Renew	Aquatic DO Post-Renew	Pre-Renew ORP	Post-Renew ORP	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Sulfide, mV Reading (mV)	Sulfide, Calc Conc (mg/L)	Comments/Observations
0	A	22.4		13.1			7.0		7.2		0.5		55.9	0.0	0.0	0.0	0.0	
	B	22.4		12.6			6.9		7.6		0.7		56.1	0.0	0.0	0.0	0.0	
	C	22.2		12.9			7.0		7.6		0.8		59.4	0.0	0.0	0.0	0.0	
	D	22.6		12.4			6.9		7.5		0.7		58.5	0.0	0.0	0.0	0.0	
1	A	22.4	22.5	12.7		6.9	7.0	7.5	7.3	0.9	0.8	53.6	54.1	0.0	0.0	0.0	0.0	
	B	22.4	22.5	12.8		7.0	6.9	7.6	7.8	0.7	0.8	55.1	54.9	0.0	0.0	0.0	0.0	
	C	22.6	22.7	12.8		6.9	6.9	7.8	7.8	0.7	0.8	53.6	54.4	0.0	0.0	0.0	0.0	
	D	22.7	22.5	12.9		7.0	6.9	8.0	7.7	0.9	0.9	53.2	55.5	0.0	0.0	0.0	0.0	
2	A	22.5	22.5	12.8		6.9	6.8	7.2	7.8	0.8	0.8	53.6	54.7	0.0	0.0	0.0	0.0	
	B	22.5	22.5	12.6		7.0	6.9	7.6	7.2	0.6	0.6	56.0	57.2	0.0	0.0	0.0	0.0	
	C	22.4	22.5	12.8		6.9	6.9	7.9	7.7	0.8	0.5	52.9	53.8	0.0	0.0	0.0	0.0	
	D	22.6	22.7	12.7		7.0	6.9	7.5	7.7	0.8	0.7	53.8	54.9	0.0	0.0	0.0	0.0	
3	A	22.6	22.5	12.8		6.9	6.8	7.7	7.8	0.6	0.7	56.1	57.1	0.0	0.0	0.0	0.0	
	B	22.5	22.4	13.1		6.9	6.9	7.4	7.6	0.6	0.6	57.3	58.1	0.0	0.0	0.0	0.0	
	C	22.9	22.7	12.6		6.9	6.9	7.8	7.5	0.7	0.6	56.9	57.1	0.0	0.0	0.0	0.0	
	D	22.9	22.9	12.8		7.0	6.9	7.4	7.6	0.9	0.8	55.2	57.1	0.0	0.0	0.0	0.0	
4	A	22.5	22.7	12.8		6.9	6.8	7.9	7.6	0.7	0.7	56.2	57.1	0.0	0.0	0.0	0.0	
	B	22.5	22.7	12.8		7.0	6.9	7.8	7.6	0.8	0.9	57.0	58.2	0.0	0.0	0.0	0.0	
	C	22.5	22.4	13.1		7.0	6.9	7.7	7.6	0.7	0.6	54.5	56.3	0.0	0.0	0.0	0.0	
	D	22.5	22.7	13.1		6.9	6.9	7.7	7.9	0.6	0.5	56.2	57.2	0.0	0.0	0.0	0.0	
5	A	22.5	22.5	12.5		6.9	6.9	7.4	7.9	0.6	0.9	54.8	55.8	0.0	0.0	0.0	0.0	
	B	22.6	22.5	12.5		6.9	6.9	7.6	7.9	0.7	0.9	54.5	57.2	0.0	0.0	0.0	0.0	
	C	22.7	22.4	12.5		7.0	6.9	7.6	7.7	0.9	0.7	52.9	53.8	0.0	0.0	0.0	0.0	
	D	22.5	22.7	12.2		6.9	6.8	7.7	7.9	0.5	0.7	55.5	57.2	0.0	0.0	0.0	0.0	
6	A	22.5	22.4	12.7		7.0	7.0	7.3	7.4	0.9	0.8	52.8	54.5	0.0	0.0	0.0	0.0	
	B	22.5	22.4	12.6		6.9	6.9	7.5	7.8	0.5	0.7	55.1	57.3	0.0	0.0	0.0	0.0	
	C	22.6	22.5	12.6		7.0	6.9	7.4	7.7	0.6	0.9	52.2	54.5	0.0	0.0	0.0	0.0	
	D	22.5	22.4	12.7		6.9	6.9	7.6	7.7	0.8	0.7	52.8	55.6	0.0	0.0	0.0	0.0	
7	A	22.5	22.4	12.7		6.9	6.9	7.4	7.5	0.6	0.6	53.8	54.7	0.0	0.0	0.0	0.0	
	B	22.6	22.7	12.7		6.9	6.9	7.4	7.6	0.9	0.6	55.2	57.4	0.0	0.0	0.0	0.0	
	C	22.5	22.4	12.8		7.0	6.9	7.7	7.9	0.6	0.9	54.8	55.8	0.0	0.0	0.0	0.0	
	D	22.6	22.5	12.9		6.9	6.8	7.5	7.2	0.8	0.7	52.5	54.8	0.0	0.0	0.0	0.0	
8	A	22.8	22.5	13.0		6.9	6.8	7.5	7.4	0.6	0.7	52.6	54.6	0.0	0.0	0.0	0.0	
	B	22.7	22.5	12.6		7.0	6.9	7.2	7.5	0.5	0.6	54.9	56.1	0.0	0.0	0.0	0.0	
	C	22.5	22.4	12.6		6.9	6.9	7.3	6.9	0.5	0.8	53.6	53.6	0.0	0.0	0.0	0.0	
	D	22.5	22.5	12.6		6.9	6.9	7.7	7.8	0.8	0.6	55.5	52.7	0.0	0.0	0.0	0.0	
9	A	22.5	22.5	12.4		6.9	6.8	7.6	7.3	0.6	0.5	56.1	57.2	0.0	0.0	0.0	0.0	
	B	22.4	22.4	12.6		6.9	6.9	7.5	7.3	0.7	0.6	55.4	57.1	0.0	0.0	0.0	0.0	
	C	22.5	22.4	12.5		6.9	6.9	7.7	7.5	0.7	0.8	53.6	54.7	0.0	0.0	0.0	0.0	
	D	22.5	22.5	12.5		7.0	6.9	7.0	6.9	0.6	0.5	53.8	54.8	0.0	0.0	0.0	0.0	
10	A	22.4	22.4			6.9		7.5		0.7		55.1		0.0	0.0	0.0	0.0	
	B	22.6	22.5			7.0		7.6		0.7		56.1		0.0	0.0	0.0	0.0	
	C	22.6	22.5			7.0		6.9		0.5		55.2		0.0	0.0	0.0	0.0	
	D	22.5	22.4			6.9		6.9		0.5		56.1		0.0	0.0	0.0	0.0	
	MIN	22.2	22.4	12.2	0	6.9	6.8	6.9	6.9	0.5	0.5	52.2	52.7	0.0	0.00	0.0	0.00	
	MAX	22.9	22.9	13.1	0	7.0	7.0	8.0	7.9	0.9	0.9	57.3	59.4	0.0	0.00	0.0	0.00	
	MEAN	22.5	22.5	12.7	N/A	6.9	6.9	7.5	7.6	0.7	0.7	54.7	55.9	0.0	0.00	0.0	0.00	
	SEM	0.02	0.02	0.03	N/A	0.01	0.01	0.04	0.04	0.02	0.02	0.22	0.25	0.00	0.000	0.00	0.000	

Temp Range = AM19-23 PM 10-14
Light Intensity = 0 through SD10 then 4000-6000 lux

FEL

IMAM01-00420

Media Chemistry

Test Day	Test Date	Tech Initials	Treatment	Rep	Conductivity (µS/cm)	Alkalinity (mg/L)	Hardness (mg/L)	Ammonia-Nitrogen (mg/L)	Total Fe (mg/L)	Nitrate (mg/L)	Sulfate (mg/L)	Phosphate (mg/L)	Total Residual Oxidants (mg/L)
0	11/3/17	DJF	1 - HS-1 (1:4)	A	473	4	100	10.8	0.82	38	56	7.4	0.00
		DJF	2 - 0.3 mg/L S^{2-} 0.8 mg/L Fe		470	0	106	10.6	0.84	40	52	7.5	0.00
		DJF	3 - 1.56 mg/L S^{2-} 0.8 mg/L Fe		484	0	108	10.4	0.79	36	54	7.6	0.00
		DJF	4 - 3.12 mg/L S^{2-} 0.8 mg/L Fe		476	4	104	10.8	0.83	42	50	7.8	0.00
		DJF	5 - 7.80 mg/L S^{2-} 0.8 mg/L Fe		481	4	108	11.2	0.78	48	56	7.2	0.00
		DJF	6 - HS-1 (1:4) 2.8 mg/L Fe		469	0	104	11.5	2.91	44	52	7.6	0.00
		DJF	7 - 0.3 mg/L S^{2-} 2.8 mg/L Fe		472	4	96	11.2	2.84	46	54	7.5	0.00
		DJF	8 - 1.56 mg/L S^{2-} 2.8 mg/L Fe		475	4	100	10.8	2.81	42	56	7.8	0.00
		DJF	9 - 3.12 mg/L S^{2-} 2.8 mg/L Fe		478	0	104	10.4	2.83	48	58	7.4	0.00
		DJF	10 - 7.80 mg/L S^{2-} 2.8 mg/L Fe		480	0	108	10.4	2.78	44	56	7.6	0.00
		DJF	11 - 100 mg/L BA		472	0	104	10.6	0.81	46	52	7.2	0.00
0	11/3/17	DJF	1 - HS-1 (1:4)	B	464	0	104	10.8	0.81	42	54	7.0	0.00
		DJF	2 - 0.3 mg/L S^{2-} 0.8 mg/L Fe		468	4	108	11.2	0.79	44	50	7.2	0.00
		DJF	3 - 1.56 mg/L S2- 0.8 mg/L Fe		472	4	100	11.4	0.76	48	52	7.6	0.00
		DJF	4 - 3.12 mg/L S2- 0.8 mg/L Fe		470	0	96	10.9	0.84	46	56	7.1	0.00
		DJF	5 - 7.80 mg/L S2- 0.8 mg/L Fe		468	0	100	11.0	0.83	42	58	7.3	0.00
		DJF	6 - HS-1 (1:4) 2.8 mg/L Fe		478	4	108	10.8	2.78	40	52	7.5	0.00
		DJF	7 - 0.3 mg/L S^{2-} 2.8 mg/L Fe		468	4	104	10.6	2.82	44	56	7.6	0.00
		DJF	8 - 1.56 mg/L S^{2-} 2.8 mg/L Fe		470	4	100	10.9	2.83	42	54	7.3	0.00
		DJF	9 - 3.12 mg/L S^{2-} 2.8 mg/L Fe		466	0	96	11.2	2.84	40	50	7.4	0.00
		DJF	10 - 7.80 mg/L S^{2-} 2.8 mg/L Fe		472	0	104	11.0	2.76	46	48	7.5	0.00
		DJF	11 - 100 mg/L BA		476	0	108	11.4	0.83	48	52	7.2	0.00
10	11/13/17	DJF	1 - HS-1 (1:4)	C	472	0	104	10.6	0.82	44	52	7.2	0.00
		DJF	2 - 0.3 mg/L S^{2-} 0.8 mg/L Fe		475	4	108	10.8	0.84	40	50	7.3	0.00
		DJF	3 - 1.56 mg/L S2- 0.8 mg/L Fe		480	0	112	10.5	0.83	44	56	7.5	0.00
		DJF	4 - 3.12 mg/L S2- 0.8 mg/L Fe		469	0	100	10.6	0.79	48	58	7.1	0.00
		DJF	5 - 7.80 mg/L S2- 0.8 mg/L Fe		473	0	104	10.8	0.82	46	54	7.3	0.00
		DJF	6 - HS-1 (1:4) 2.8 mg/L Fe		475	4	108	10.7	2.84	42	50	7.5	0.00
		DJF	7 - 0.3 mg/L S^{2-} 2.8 mg/L Fe		470	4	100	10.5	2.86	42	52	7.2	0.00
		DJF	8 - 1.56 mg/L S^{2-} 2.8 mg/L Fe		473	0	100	10.3	2.83	46	56	7.2	0.00
		DJF	9 - 3.12 mg/L S^{2-} 2.8 mg/L Fe		476	0	104	10.6	2.81	48	56	7.4	0.00
		DJF	10 - 7.80 mg/L S^{2-} 2.8 mg/L Fe		475	0	108	10.8	2.86	48	52	7.6	0.00
		DJF	11 - 100 mg/L BA		479	0	112	10.7	0.81	40	54	7.1	0.00
10	11/13/17	DJF	1 - HS-1 (1:4)	D	470	4	104	10.4	0.81	42	54	7.0	0.00
		DJF	2 - 0.3 mg/L S^{2-} 0.8 mg/L Fe		474	4	104	10.6	0.79	44	58	7.4	0.00
		DJF	3 - 1.56 mg/L S2- 0.8 mg/L Fe		476	0	108	10.2	0.83	40	56	7.2	0.00
		DJF	4 - 3.12 mg/L S2- 0.8 mg/L Fe		479	0	100	10.8	0.85	48	50	7.0	0.00
		DJF	5 - 7.80 mg/L S2- 0.8 mg/L Fe		480	0	104	10.7	0.80	50	52	6.9	0.00
		DJF	6 - HS-1 (1:4) 2.8 mg/L Fe		468	4	112	10.3	2.84	46	54	7.0	0.00
		DJF	7 - 0.3 mg/L S^{2-} 2.8 mg/L Fe		472	0	108	10.5	2.86	46	56	7.4	0.00
		DJF	8 - 1.56 mg/L S^{2-} 2.8 mg/L Fe		474	0	108	10.7	2.81	42	48	7.6	0.00
		DJF	9 - 3.12 mg/L S^{2-} 2.8 mg/L Fe		478	0	100	10.9	2.88	48	52	7.2	0.00
		DJF	10 - 7.80 mg/L S^{2-} 2.8 mg/L Fe		470	4	104	10.7	2.87	46	50	7.1	0.00
		DJF	11 - 100 mg/L BA		480	4	100	10.8	0.83	42	56	7.5	0.00

Page No.____

FEL

FEL

IMAM01-00420
Media Chemistry

Test Day	Test Date	Tech Initials	Treatment	Rep	Conductivity (µS/cm)	Alkalinity (mg/L)	Hardness (mg/L)	Ammonia-Nitrogen (mg/L)	Total Fe (mg/L)	Nitrate (mg/L)	Sulfate (mg/L)	Phosphate (mg/L)	Total Residual Oxidants (mg/L)
			1 - HS-1 (1:4)	Mean	469.8	2.0	103.0	10.7	0.8	41.5	54.0	7.2	0.0
				SEM	2.0	1.2	1.0	0.1	0.0	1.3	0.8	0.1	0.0
				Min	464.0	0.0	100.0	10.4	0.8	38.0	52.0	7.0	0.0
				Max	473.0	4.0	104.0	10.8	0.8	44.0	56.0	7.4	0.0
			2 - 0.3 mg/L S^{2-} 0.8 mg/L Fe	Mean	471.8	3.0	106.5	10.8	0.8	42.0	52.5	7.4	0.0
				SEM	1.7	1.0	1.0	0.1	0.0	1.2	1.9	0.1	0.0
				Min	468.0	0.0	104.0	10.6	0.8	40.0	50.0	7.2	0.0
				Max	475.0	4.0	108.0	11.2	0.8	44.0	58.0	7.5	0.0
			3 - 1.56 mg/L S2- 0.8 mg/L Fe	Mean	478.0	1.0	107.0	10.6	0.8	42.0	54.5	7.5	0.0
				SEM	2.6	1.0	2.5	0.3	0.0	2.6	1.0	0.1	0.0
				Min	472.0	0.0	100.0	10.2	0.8	36.0	52.0	7.2	0.0
				Max	484.0	4.0	112.0	11.4	0.8	48.0	56.0	7.6	0.0
			4 - 3.12 mg/L S2- 0.8 mg/L Fe	Mean	473.5	1.0	100.0	10.8	0.8	46.0	53.5	7.3	0.0
				SEM	2.4	1.0	1.6	0.1	0.0	1.4	2.1	0.2	0.0
				Min	469.0	0.0	96.0	10.6	0.8	42.0	50.0	7.0	0.0
				Max	479.0	4.0	104.0	10.9	0.9	48.0	58.0	7.8	0.0
			5 - 7.80 mg/L S2- 0.8 mg/L Fe	Mean	475.5	1.0	104.0	10.9	0.8	46.5	55.0	7.2	0.0
				SEM	3.1	1.0	1.6	0.1	0.0	1.7	1.3	0.1	0.0
				Min	468.0	0.0	100.0	10.7	0.8	42.0	52.0	6.9	0.0
				Max	481.0	4.0	108.0	11.2	0.8	50.0	58.0	7.3	0.0
			6 - HS-1 (1:4) 2.8 mg/L Fe	Mean	472.5	3.0	108.0	10.8	2.8	43.0	52.0	7.4	0.0
				SEM	2.4	1.0	1.6	0.2	0.0	1.3	0.8	0.1	0.0
				Min	468.0	0.0	104.0	10.3	2.8	40.0	50.0	7.0	0.0
				Max	478.0	4.0	112.0	11.5	2.9	46.0	54.0	7.6	0.0
			7 - 0.3 mg/L S^{2-} 2.8 mg/L Fe	Mean	470.5	3.0	102.0	10.7	2.8	44.5	54.5	7.4	0.0
				SEM	1.0	1.0	2.6	0.2	0.0	1.0	1.0	0.1	0.0
				Min	468.0	0.0	96.0	10.5	2.8	42.0	52.0	7.2	0.0
				Max	472.0	4.0	108.0	11.2	2.9	46.0	56.0	7.6	0.0
			8 - 1.56 mg/L S^{2-} 2.8 mg/L Fe	Mean	473.0	2.0	102.0	10.7	2.8	43.0	53.5	7.5	0.0
				SEM	1.1	1.2	2.0	0.1	0.0	1.0	1.9	0.1	0.0
				Min	470.0	0.0	100.0	10.3	2.8	42.0	48.0	7.2	0.0
				Max	475.0	4.0	108.0	10.9	2.8	46.0	56.0	7.8	0.0
			9 - 3.12 mg/L S^{2-} 2.8 mg/L Fe	Mean	474.5	0.0	101.0	10.8	2.8	46.0	54.0	7.4	0.0
				SEM	2.9	0.0	1.9	0.2	0.0	2.0	1.8	0.1	0.0
				Min	466.0	0.0	96.0	10.4	2.8	40.0	50.0	7.2	0.0
				Max	478.0	0.0	104.0	11.2	2.9	48.0	58.0	7.4	0.0
			10 - 7.80 mg/L S^{2-} 2.8 mg/L Fe	Mean	474.3	1.0	106.0	10.7	2.8	46.0	51.5	7.5	0.0
				SEM	2.2	1.0	1.2	0.1	0.0	0.8	1.7	0.1	0.0
				Min	470.0	0.0	104.0	10.4	2.8	44.0	48.0	7.1	0.0
				Max	480.0	4.0	108.0	11.0	2.9	48.0	56.0	7.6	0.0
			11 - 100 mg/L BA	Mean	476.8	1.0	106.0	10.9	0.8	44.0	53.5	7.3	0.0
				SEM	1.8	1.0	2.6	0.2	0.0	1.8	1.0	0.1	0.0
				Min	472.0	0.0	100.0	10.6	0.8	40.0	52.0	7.1	0.0
				Max	480.0	4.0	112.0	11.4	0.8	48.0	56.0	7.5	0.0

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FEL

IMAM01-00420 - Endpoint Data Summary

Treatment	Rep	Per Replicate							
		Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emerg-ence (%)	Seedling Survival (n)	Survival (%)	Phytotox: Abnormal Appearance (n)	Phytotox: Abnormal Appearance (%)
HS-1 (1:4) 0.8 mg/L Fe	A	40	100.0	12	30.0	12.0	100.0	0	0.0
	B	40	100.0	10	25.0	10.0	100.0	0	0.0
	C	40	100.0	13	32.5	13.0	100.0	0	0.0
	D	40	100.0	14	35.0	14.0	100.0	0	0.0
	Mean:	**40**	**100**	**12.3**	**30.6**	**12.3**	**100.0**	**0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.85**	**2.13**	**0.85**	**0.0**	**0.0**	**0.0**
0.3 mg/L Sulfide 0.8 mg/L Fe	A	40	100.0	14	35.0	14.0	100.0	0	0.0
	B	40	100.0	10	25.0	10.0	100.0	0	0.0
	C	40	100.0	12	30.0	12.0	100.0	0	0.0
	D	40	100.0	13	32.5	13.0	100.0	0	0.0
	Mean:	**40**	**100**	**12.3**	**30.6**	**12.3**	**100**	**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.85**	**2.13**	**0.85**	**0.0**	**0.00**	**0.0**
1.56 mg/L Sulfide 0.8 mg/L Fe	A	40	100.0	12	30.0	12.0	100.0	0	0.0
	B	40	100.0	13	32.5	13.0	100.0	0	0.0
	C	40	100.0	12	30.0	12.0	100.0	0	0.0
	D	40	100.0	10	25.0	10.0	100.0	0	0.0
	Mean:	**40**	**100**	**11.8**	**29.4**	**11.8**	**100**	**0**	**0**
	SEM:	**0.0**	**0.0**	**0.63**	**1.57**	**0.63**	**0.0**	**0.0**	**0.0**
3.12 mg/L Sulfide 0.8 mg/L Fe	A	40	100.0	8	20.0	8.0	100.0	0	0.0
	B	40	100.0	9	22.5	9.0	100.0	0	0.0
	C	40	100.0	8	20.0	8.0	100.0	0	0.0
	D	40	100.0	9	22.5	9.0	100.0	0	0.0
	Mean:	**40**	**100**	**8.5**	**21.3**	**8.5**	**100**	**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**	**0.00**	**0.0**

FEL

IMAM01-00420 - Endpoint Data Summary

Treatment	Rep	Per Replicate: Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emerg-ence (%)	Seedling Survival (n)	Survival (%)	Phytotox: Abnormal Appearance (n)	Phytotox: Abnormal Appearance (%)
7.80 mg/L Sulfide 0.8 mg/L Fe	A	40	100.0	4	10.0	4.0	100.0	0	0.0
	B	40	100.0	4	10.0	4.0	100.0	0	0.0
	C	40	100.0	3	7.5	3.0	100.0	0	0.0
	D	40	100.0	4	10.0	4.0	100.0	0	0.0
	Mean:	**40**	**100**	**3.8**	**9.4**	**3.8**	**100.0**	**0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.25**	**0.63**	**0.25**	**0.0**	**0.0**	**0.0**
HS-1 (1:4) 2.8 mg/L Fe	A	40	100.0	12	30.0	12.0	100.0	0	0.0
	B	40	100.0	14	35.0	14.0	100.0	0	0.0
	C	40	100.0	15	37.5	15.0	100.0	0	0.0
	D	40	100.0	11	27.5	11.0	100.0	0	0.0
	Mean:	**40**	**100**	**13.0**	**32.5**	**13.0**	**100**	**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.91**	**2.28**	**0.91**	**0.0**	**0.00**	**0.0**
0.3 mg/L Sulfide 2.8 mg/L Fe	A	40	100.0	12	30.0	12.0	100.0	0	0.0
	B	40	100.0	14	35.0	14.0	100.0	0	0.0
	C	40	100.0	13	32.5	13.0	100.0	0	0.0
	D	40	100.0	12	30.0	12.0	100.0	0	0.0
	Mean:	**40**	**100**	**12.8**	**31.9**	**12.8**	**100**	**0**	**0**
	SEM:	**0.0**	**0.0**	**0.48**	**1.20**	**0.48**	**0.0**	**0.0**	**0.0**
1.56 mg/L Sulfide 2.8 mg/L Fe	A	40	100.0	10	25.0	10.0	100.0	0	0.0
	B	40	100.0	10	25.0	10.0	100.0	0	0.0
	C	40	100.0	9	22.5	9.0	100.0	0	0.0
	D	40	100.0	9	22.5	9.0	100.0	0	0.0
	Mean:	**40**	**100**	**9.5**	**23.8**	**9.5**	**100**	**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**	**0.00**	**0.0**

FEL

IMAM01-00420 - Endpoint Data Summary

Treatment	Rep	Per Replicate							
		Activated Seed (n)	Activation (%)	Mesocotyl Emerged (n)	Mesocotyl Emerg-ence (%)	Seedling Survival (n)	Survival (%)	Phytotox: Abnormal Appearance (n)	Phytotox: Abnormal Appearance (%)
3.12 mg/L Sulfide 2.8 mg/L Fe	A	40	100.0	12	30.0	12.0	100.0	0	0.0
	B	40	100.0	12	30.0	12.0	100.0	0	0.0
	C	40	100.0	13	32.5	13.0	100.0	0	0.0
	D	40	100.0	11	27.5	11.0	100.0	0	0.0
	Mean:	**40**	**100**	**12.0**	**30.0**	**12.0**	**100.0**	**0**	**0.0**
	SEM:	**0.0**	**0.0**	**0.41**	**1.02**	**0.41**	**0.0**	**0.0**	**0.0**
7.80 mg/L Sulfide 2.8 mg/L Fe	A	40	100.0	7	17.5	7.0	100.0	0	0.0
	B	40	100.0	7	17.5	7.0	100.0	0	0.0
	C	40	100.0	8	20.0	8.0	100.0	0	0.0
	D	40	100.0	7	17.5	7.0	100.0	0	0.0
	Mean:	**40**	**100**	**7.3**	**18.1**	**7.3**	**100**	**0.0**	**0**
	SEM:	**0.0**	**0.0**	**0.25**	**0.63**	**0.25**	**0.0**	**0.00**	**0.0**
HS-1 (1:4) 100 mg/L BA	A	40	100.0	3	7.5	3.0	100.0	3	100.0
	B	40	100.0	4	10.0	4.0	100.0	4	100.0
	C	40	100.0	4	10.0	4.0	100.0	4	100.0
	D	40	100.0	3	7.5	3.0	100.0	3	100.0
	Mean:	**40**	**100**	**3.5**	**8.8**	**3.5**	**100**	**3.5**	**100**
	SEM:	**0.0**	**0.0**	**0.29**	**0.72**	**0.29**	**0.0**	**0.3**	**0.0**

FEL

	Median Emergence Time (d)										
	HS-1	100 mg/L BA	0.3 mg/L S^{2-} 0.8 mg/L Fe	1.56 mg/L S^{2-} 0.8 mg/L Fe	3.12 mg/L S^{2-} 0.8 mg/L Fe	7.8 mg/L S^{2-} 0.8 mg/L Fe	HS-1 2.8 mg/L Fe	0.3 mg/L S^{2-} 2.8 mg/L Fe	1.56 mg/L S^{2-} 2.8 mg/L Fe	3.12 mg/L S^{2-} 2.8 mg/L Fe	7.8 mg/L S^{2-} 2.8 mg/L Fe
Rep A	7	>10	6	7	>10	>10	7	7	>10	8	>10
Rep B	>10	>10	6	6	>10	>10	6	6	>10	8	>10
Rep C	7	>10	>10	7	>10	>10	6	7	>10	8	>10
Rep D	6	>10	7	>10	>10	>10	>10	7	>10	>10	>10
Median	**7**	**>10**	**6.5**	**7**	**>10**	**>10**	**6.5**	**7**	**>10**	**8**	**>10**
SEM	**1.1**	**0.0**	**1.2**	**1.1**	**0.0**	**0.0**	**1.2**	**0.3**	**0.0**	**0.8**	**0.0**

Descriptive Statistics: Tuesday, November 14, 2017, 3:20:05 PM

Data source: Emergence in 00420_Stats.JNB

Column	Size	Missing	Mean	Std Dev	Std. Error	C.I. of Mean
HS-1	4	0	0.306	0.043	0.021	0.068
0.3 mg/L	4	0	0.306	0.043	0.021	0.068
1.56 mg/L	4	0	0.294	0.032	0.016	0.050
3.12 mg/L	4	0	0.213	0.014	0.007	0.023
7.8 mg/L	4	0	0.094	0.013	0.006	0.020
HS-1 2.8	4	0	0.325	0.046	0.023	0.073
0.3 mg/L 2.8	4	0	0.319	0.024	0.012	0.038
1.56 mg/L 2.8	4	0	0.237	0.014	0.007	0.023
3.12 mg/L 2.8	4	0	0.300	0.020	0.010	0.033
7.8 mg/L 2.8	4	0	0.181	0.013	0.006	0.020
100 mg/L BA	4	0	0.088	0.014	0.007	0.023

Column	Range	Max	Min	Median	10%	90%
HS-1	0.100	0.350	0.250	0.313	0.250	0.350
0.3 mg/L	0.100	0.350	0.250	0.313	0.250	0.350
1.56 mg/L	0.075	0.325	0.250	0.300	0.250	0.325
3.12 mg/L	0.025	0.225	0.200	0.213	0.200	0.225
7.8 mg/L	0.025	0.100	0.075	0.100	0.075	0.100
HS-1 2.8	0.100	0.375	0.275	0.325	0.275	0.375
0.3 mg/L 2.8	0.050	0.350	0.300	0.313	0.300	0.350
1.56 mg/L 2.8	0.025	0.250	0.225	0.237	0.225	0.250
3.12 mg/L 2.8	0.050	0.325	0.275	0.300	0.275	0.325
7.8 mg/L 2.8	0.025	0.200	0.175	0.175	0.175	0.200
100 mg/L BA	0.025	0.100	0.075	0.088	0.075	0.100

Column	Skewness	Kurtosis	K-S Dist.	K-S Prob.	SWilk W	SWilk Prob
HS-1	-0.753	0.343	0.192	0.657	0.971	0.85
0.3 mg/L	-0.753	0.343	0.192	0.657	0.971	0.85
1.56 mg/L	-1.129	2.227	0.329	0.138	0.895	0.406
3.12 mg/L	0.000	-6.000	0.307	0.203	0.729	0.024
7.8 mg/L	-2.000	4.000	0.441	0.006	0.63	0.001
HS-1 2.8	0.000	-3.300	0.208	0.606	0.95	0.714
0.3 mg/L 2.8	0.855	-1.289	0.283	0.289	0.863	0.272
1.56 mg/L 2.8	0.000	-6.000	0.307	0.203	0.729	0.024
3.12 mg/L 2.8	0.000	1.500	0.25	0.432	0.945	0.683
7.8 mg/L 2.8	2.000	4.000	0.441	0.006	0.63	0.001
100 mg/L BA	0.000	-6.000	0.307	0.203	0.729	0.024

Column	Sum	Sum of Squares
HS-1	1.225	0.381
0.3 mg/L	1.225	0.381
1.56 mg/L	1.175	0.348
3.12 mg/L	0.85	0.181
7.8 mg/L	0.375	0.0356
HS-1 2.8	1.3	0.429
0.3 mg/L 2.8	1.275	0.408
1.56 mg/L 2.8	0.95	0.226
3.12 mg/L 2.8	1.2	0.361
7.8 mg/L 2.8	0.725	0.132
100 mg/L BA	0.35	0.0313

One Way Analysis of Variance	Tuesday, November 14, 2017, 3:30:25 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk)	Passed	(P = 0.162)
Equal Variance Test:	Passed	(P = 0.547)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
HS-1	4	0	0.586	0.047	0.023
0.3 mg/L	4	0	0.586	0.047	0.023
1.56 mg/L	4	0	0.572	0.035	0.018
3.12 mg/L	4	0	0.479	0.018	0.009
7.8 mg/L	4	0	0.311	0.022	0.011
100 mg/L BA	4	0	0.300	0.026	0.013

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Groups	5	0.367	0.0734	62.383	<0.001
Residual	18	0.0212	0.00118		
Total	23	0.388			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

Multiple Comparisons versus Control Group (Dunnett's Method) :

Comparisons for factor:

Comparison	**Diff of Means**	**q'**	**P**	**P<0.050**
HS-1 vs. 100 mg/L BA	0.286	11.798	--	Yes
HS-1 vs. 7.8 mg/L	0.275	11.341	--	Yes
HS-1 vs. 3.12 mg/L	0.107	4.403	--	Yes
HS-1 vs. 1.56 mg/L	0.0134	0.551	--	No
HS-1 vs. 0.3 mg/L	0.000	0.000	--	Do Not Test

Note: The P values for Dunnett's and Duncan's tests are currently unavailable except for reporting that the P's are greater or less than the critical values of .05 and .01.

A result of "Do Not Test" occurs for a comparison when no significant difference is found between two means that enclose that comparison. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1 (4 vs. 3 and 3 vs. 2 are enclosed by 4 vs. 2: 4 3 2 1). Note that not testing the enclosed means is a procedural rule, and a result of Do Not Test should be treated as if there is no significant difference between the means, even though one may appear to exist.

One Way Analysis of Variance Tuesday, November 14, 2017, 3:32:11 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.125)

Equal Variance Test: Passed (P = 0.510)

Group Name	N	Missing	Mean	Std Dev	SEM
HS-1	4	0	0.586	0.047	0.023
0.3 mg/L	4	0	0.586	0.047	0.023
1.56 mg/L	4	0	0.572	0.035	0.018
3.12 mg/L	4	0	0.479	0.018	0.009
7.8 mg/L	4	0	0.311	0.022	0.011

Source of Variation	DF	SS	MS	F	P
Between Groups	4	0.224	0.056	43.726	<0.001
Residual	15	0.0192	0.00128		
Total	19	0.243			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

Multiple Comparisons versus Control Group (Dunnett's Method) :

Comparisons for factor:

Comparison	Diff of Means	q'	P	P<0.050
HS-1 vs. 7.8 mg/L	0.275	10.869	--	Yes
HS-1 vs. 3.12 mg/L	0.107	4.220	--	Yes
HS-1 vs. 1.56 mg/L	0.0134	0.528	--	No
HS-1 vs. 0.3 mg/L	0.000	0.000	--	Do Not Test

Note: The P values for Dunnett's and Duncan's tests are currently unavailable except for reporting that the P's are greater or less than the critical values of .05 and .01.

A result of "Do Not Test" occurs for a comparison when no significant difference is found between two means that enclose that comparison. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1 (4 vs. 3 and 3 vs. 2 are enclosed by 4 vs. 2: 4 3 2 1). Note that not testing the enclosed means is a procedural rule, and a result of Do Not Test should be treated as if there is no significant difference between the means, even though one may appear to exist.

One Way Analysis of Variance Tuesday, November 14, 2017, 3:32:51 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.944)

Equal Variance Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 3:32:51 PM

Data source: Emergence in 00420_Stats.JNB

Group	N	Missing	Median	25%	75%
HS-1 2.8	4	0	0.606	0.559	0.653
0.3 mg/L 2.8	4	0	0.593	0.58	0.626
1.56 mg/L 2.8	4	0	0.509	0.494	0.524
3.12 mg/L 2.8	4	0	0.58	0.559	0.6
7.8 mg/L 2.8	4	0	0.432	0.432	0.456

H = 15.349 with 4 degrees of freedom. (P = 0.004)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.004)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

Multiple Comparisons versus Control Group (Dunn's Method) :

Comparison	Diff of Ranks	Q	P<0.05
7.8 mg/L 2.8 vs HS-1 2.8	12.750	3.048	Yes
1.56 mg/L 2.8 vs HS-1 2.8	8.750	2.092	No
3.12 mg/L 2.8 vs HS-1 2.8	2.250	0.538	Do Not Test
0.3 mg/L 2.8 vs HS-1 2.8	0.000	0.000	Do Not Test

Note: The multiple comparisons on ranks do not include an adjustment for ties.

t-test Tuesday, November 14, 2017, 3:51:19 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.463)

Equal Variance Test: Passed (P = 0.711)

Group Name	N	Missing	Mean	Std Dev	SEM
HS-1	4	0	0.586	0.0468	0.0234
HS-1 2.8	4	0	0.606	0.0488	0.0244

Difference -0.0202

t = -0.598 with 6 degrees of freedom. (P = 0.572)

95 percent confidence interval for difference of means: -0.103 to 0.0625

The difference in the mean values of the two groups is not great enough to reject the possibility that the difference is due to random sampling variability. There is not a statistically significant difference between the input groups (P = 0.572).

Power of performed test with alpha = 0.050: 0.050

The power of the performed test (0.050) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.

t-test Tuesday, November 14, 2017, 3:51:39 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapir Passed (P = 0.902)

Equal Variance Test: Passed (P = 0.383)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
0.3 mg/L	4	0	0.586	0.0468	0.0234
0.3 mg/L 2.8	4	0	0.6	0.0256	0.0128

Difference -0.0140

t = -0.525 with 6 degrees of freedom. (P = 0.618)

95 percent confidence interval for difference of means: -0.0793 to 0.0513

The difference in the mean values of the two groups is not great enough to reject the possibility that the difference is due to random sampling variability. There is not a statistically significant difference between the input groups (P = 0.618).

Power of performed test with alpha = 0.050: 0.050

The power of the performed test (0.050) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.

t-test Tuesday, November 14, 2017, 3:51:57 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.473)

Equal Variance Test: Passed (P = 0.666)

Group Name	N	Missing	Mean	Std Dev	SEM
1.56 mg/L	4	0	0.572	0.0349	0.0175
1.56 mg/L 2.8	4	0	0.509	0.017	0.00848

Difference 0.0635

t = 3.270 with 6 degrees of freedom. (P = 0.017)

95 percent confidence interval for difference of means: 0.0160 to 0.111

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = 0.017).

Power of performed test with alpha = 0.050: 0.744

t-test Tuesday, November 14, 2017, 3:52:12 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.735)

Equal Variance Test: Passed (P = 0.843)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
3.12 mg/L	4	0	0.479	0.0176	0.00882
3.12 mg/L 2.8	4	0	0.579	0.0223	0.0111

Difference -0.1010

t = -7.073 with 6 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: -0.135 to -0.0658

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

t-test Tuesday, November 14, 2017, 3:52:26 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.334)

Equal Variance Test: Passed (P = 0.830)

Group Name	N	Missing	Mean	Std Dev	SEM
7.8 mg/L	4	0	0.311	0.0222	0.0111
7.8 mg/L 2.8	4	0	0.440	0.016	0.00801

Difference -0.1290

t = -9.428 with 6 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: -0.162 to -0.0955

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

t-test Tuesday, November 14, 2017, 3:52:42 PM

Data source: Emergence in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.600)

Equal Variance Test: Passed (P = 0.406)

Group Name	N	Missing	Mean	Std Dev	SEM
HS-1	4	0	0.586	0.0468	0.0234
100 mg/L BA	4	0	0.300	0.0256	0.0128

Difference 0.286

t = 10.727 with 6 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: 0.221 to 0.351

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

Descriptive Statistics: Tuesday, November 14, 2017, 3:20:59 PM

Data source: Survival in 00420_Stats.JNB

Column	Size	Missing	Mean	Std Dev	Std. Error	C.I. of Mean
HS-1	4	0	1.000	0.000	0.000	0.000
0.3 mg/L	4	0	1.000	0.000	0.000	0.000
1.56 mg/L	4	0	1.000	0.000	0.000	0.000
3.12 mg/L	4	0	1.000	0.000	0.000	0.000
7.8 mg/L	4	0	1.000	0.000	0.000	0.000
HS-1 2.8	4	0	1.000	0.000	0.000	0.000
0.3 mg/L 2.8	4	0	1.000	0.000	0.000	0.000
1.56 mg/L 2.8	4	0	1.000	0.000	0.000	0.000
3.12 mg/L 2.8	4	0	1.000	0.000	0.000	0.000
7.8 mg/L 2.8	4	0	1.000	0.000	0.000	0.000
100 mg/L BA	4	0	1.000	0.000	0.000	0.000

Column	Range	Max	Min	Median	10%	90%
HS-1	0.000	1.000	1.000	1.000	1.000	1.000
0.3 mg/L	0.000	1.000	1.000	1.000	1.000	1.000
1.56 mg/L	0.000	1.000	1.000	1.000	1.000	1.000
3.12 mg/L	0.000	1.000	1.000	1.000	1.000	1.000
7.8 mg/L	0.000	1.000	1.000	1.000	1.000	1.000
HS-1 2.8	0.000	1.000	1.000	1.000	1.000	1.000
0.3 mg/L 2.8	0.000	1.000	1.000	1.000	1.000	1.000
1.56 mg/L 2.8	0.000	1.000	1.000	1.000	1.000	1.000
3.12 mg/L 2.8	0.000	1.000	1.000	1.000	1.000	1.000
7.8 mg/L 2.8	0.000	1.000	1.000	1.000	1.000	1.000
100 mg/L BA	0.000	1.000	1.000	1.000	1.000	1.000

Column	Skewness	Kurtosis	K-S Dist.	K-S Prob.	SWilk W	SWilk Prob
HS-1	0.000	-6.000	0	<0.001	0	<0.001
0.3 mg/L	0.000	-6.000	0	<0.001	0	<0.001
1.56 mg/L	0.000	-6.000	0	<0.001	0	<0.001
3.12 mg/L	0.000	-6.000	0	<0.001	0	<0.001
7.8 mg/L	0.000	-6.000	0	<0.001	0	<0.001
HS-1 2.8	0.000	-6.000	0	<0.001	0	<0.001
0.3 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
1.56 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
3.12 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
7.8 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
100 mg/L BA	0.000	-6.000	0	<0.001	0	<0.001

Column	Sum	Sum of Squares
HS-1	4	4
0.3 mg/L	4	4
1.56 mg/L	4	4
3.12 mg/L	4	4
7.8 mg/L	4	4
HS-1 2.8	4	4
0.3 mg/L 2.8	4	4
1.56 mg/L 2.8	4	4
3.12 mg/L 2.8	4	4
7.8 mg/L 2.8	4	4
100 mg/L BA	4	4

One Way Analysis of Variance Tuesday, November 14, 2017, 3:59:55 PM

Data source: Survival in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 3:59:55 PM

Data source: Survival in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**25%**	**75%**
HS-1	4	0	1.571	1.571	1.571
0.3 mg/L	4	0	1.571	1.571	1.571
1.56 mg/L	4	0	1.571	1.571	1.571
3.12 mg/L	4	0	1.571	1.571	1.571
7.8 mg/L	4	0	1.571	1.571	1.571
100 mg/L BA	4	0	1.571	1.571	1.571

H = 0.000 with 5 degrees of freedom. (P = 1.000)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

One Way Analysis of Variance Tuesday, November 14, 2017, 4:00:15 PM

Data source: Survival in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 4:00:15 PM

Data source: Survival in 00420_Stats.JNB

Group	N	Missing	Median	25%	75%
HS-1	4	0	1.571	1.571	1.571
0.3 mg/L	4	0	1.571	1.571	1.571
1.56 mg/L	4	0	1.571	1.571	1.571
3.12 mg/L	4	0	1.571	1.571	1.571
7.8 mg/L	4	0	1.571	1.571	1.571

H = 0.000 with 4 degrees of freedom. (P = 1.000)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

One Way Analysis of Variance Tuesday, November 14, 2017, 4:00:33 PM

Data source: Survival in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 4:00:33 PM

Data source: Survival in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**25%**	**75%**
HS-1 2.8	4	0	1.571	1.571	1.571
0.3 mg/L 2.8	4	0	1.571	1.571	1.571
1.56 mg/L 2.8	4	0	1.571	1.571	1.571
3.12 mg/L 2.8	4	0	1.571	1.571	1.571
7.8 mg/L 2.8	4	0	1.571	1.571	1.571

H = 0.000 with 4 degrees of freedom. (P = 1.000)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

Descriptive Statistics: Tuesday, November 14, 2017, 3:21:42 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Column	Size	Missing	Mean	Std Dev	Std. Error	C.I. of Mean
HS-1	4	0	0.000	0.000	0.000	0.000
0.3 mg/L	4	0	0.000	0.000	0.000	0.000
1.56 mg/L	4	0	0.000	0.000	0.000	0.000
3.12 mg/L	4	0	0.000	0.000	0.000	0.000
7.8 mg/L	4	0	0.000	0.000	0.000	0.000
HS-1 2.8	4	0	0.000	0.000	0.000	0.000
0.3 mg/L 2.8	4	0	0.000	0.000	0.000	0.000
1.56 mg/L 2.8	4	0	0.000	0.000	0.000	0.000
3.12 mg/L 2.8	4	0	0.000	0.000	0.000	0.000
7.8 mg/L 2.8	4	0	0.000	0.000	0.000	0.000
100 mg/L BA	4	0	1.000	0.000	0.000	0.000

Column	Range	Max	Min	Median	10%	90%
HS-1	0.000	0.000	0.000	0.000	0.000	0.000
0.3 mg/L	0.000	0.000	0.000	0.000	0.000	0.000
1.56 mg/L	0.000	0.000	0.000	0.000	0.000	0.000
3.12 mg/L	0.000	0.000	0.000	0.000	0.000	0.000
7.8 mg/L	0.000	0.000	0.000	0.000	0.000	0.000
HS-1 2.8	0.000	0.000	0.000	0.000	0.000	0.000
0.3 mg/L 2.8	0.000	0.000	0.000	0.000	0.000	0.000
1.56 mg/L 2.8	0.000	0.000	0.000	0.000	0.000	0.000
3.12 mg/L 2.8	0.000	0.000	0.000	0.000	0.000	0.000
7.8 mg/L 2.8	0.000	0.000	0.000	0.000	0.000	0.000
100 mg/L BA	0.000	1.000	1.000	1.000	1.000	1.000

Column	Skewness	Kurtosis	K-S Dist.	K-S Prob.	SWilk W	SWilk Prob
HS-1	0.000	-6.000	0	<0.001	0	<0.001
0.3 mg/L	0.000	-6.000	0	<0.001	0	<0.001
1.56 mg/L	0.000	-6.000	0	<0.001	0	<0.001
3.12 mg/L	0.000	-6.000	0	<0.001	0	<0.001
7.8 mg/L	0.000	-6.000	0	<0.001	0	<0.001
HS-1 2.8	0.000	-6.000	0	<0.001	0	<0.001
0.3 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
1.56 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
3.12 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
7.8 mg/L 2.8	0.000	-6.000	0	<0.001	0	<0.001
100 mg/L BA	0.000	-6.000	0	<0.001	0	<0.001

Column	Sum	Sum of Squares
HS-1	0	0
0.3 mg/L	0	0
1.56 mg/L	0	0
3.12 mg/L	0	0
7.8 mg/L	0	0
HS-1 2.8	0	0
0.3 mg/L 2.8	0	0
1.56 mg/L 2.8	0	0
3.12 mg/L 2.8	0	0
7.8 mg/L 2.8	0	0
100 mg/L BA	4	4

One Way Analysis of Variance Tuesday, November 14, 2017, 4:06:18 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 4:06:18 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**25%**	**75%**
HS-1	4	0	0.000	0.000	0.000
0.3 mg/L	4	0	0.000	0.000	0.000
1.56 mg/L	4	0	0.000	0.000	0.000
3.12 mg/L	4	0	0.000	0.000	0.000
7.8 mg/L	4	0	0.000	0.000	0.000
100 mg/L BA	4	0	1.571	1.571	1.571

H = 23.000 with 5 degrees of freedom. (P = <0.001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

Multiple Comparisons versus Control Group (Dunn's Method) :

Comparison	**Diff of Ranks**	**Q**	**P<0.05**
100 mg/L BA vs HS-1	12.000	2.400	No
0.3 mg/L vs HS-1	0.000	0.000	Do Not Test
1.56 mg/L vs HS-1	0.000	0.000	Do Not Test
3.12 mg/L vs HS-1	0.000	0.000	Do Not Test
7.8 mg/L vs HS-1	0.000	0.000	Do Not Test

Note: The multiple comparisons on ranks do not include an adjustment for ties.

One Way Analysis of Variance Tuesday, November 14, 2017, 4:06:47 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 4:06:47 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Group	N	Missing	Median	25%	75%
HS-1	4	0	0.000	0.000	0.000
0.3 mg/L	4	0	0.000	0.000	0.000
1.56 mg/L	4	0	0.000	0.000	0.000
3.12 mg/L	4	0	0.000	0.000	0.000
7.8 mg/L	4	0	0.000	0.000	0.000

H = 0.000 with 4 degrees of freedom. (P = 1.000)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

One Way Analysis of Variance Tuesday, November 14, 2017, 4:07:01 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Tuesday, November 14, 2017, 4:07:01 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**25%**	**75%**
HS-1 2.8	4	0	0.000	0.000	0.000
0.3 mg/L 2.8	4	0	0.000	0.000	0.000
1.56 mg/L 2.8	4	0	0.000	0.000	0.000
3.12 mg/L 2.8	4	0	0.000	0.000	0.000
7.8 mg/L 2.8	4	0	0.000	0.000	0.000

H = 0.000 with 4 degrees of freedom. (P = 1.000)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

t-test Tuesday, November 14, 2017, 4:07:23 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed ($P < 0.050$)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:07:23 PM

Data source: Phytotoxicity in 00420_Stats.JNB

Group	N	Missing	Median	10%	90%
HS-1	4	0	0.000	0.000	0.000
100 mg/L BA	4	0	1.571	1.571	1.571

Mann-Whitney U Statistic= 0.000

T = 10.000 n(small)= 4 n(big)= 4 P(est.)= 0.013 P(exact)= 0.029

The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference ($P = 0.029$)

Descriptive Statistics: Tuesday, November 14, 2017, 4:17:44 PM

Data source: ET30 in 00420_Stats.JNB

Column	Size	Missing	Mean	Std Dev	Std. Error	C.I. of Mean
HS-1	4	0	7.750	2.217	1.109	3.528
0.3 mg/L	4	0	7.750	2.217	1.109	3.528
1.56 mg/L	4	0	7.750	2.217	1.109	3.528
3.12 mg/L	4	0	11.000	0.000	0.000	0.000
7.8 mg/L	4	0	11.000	0.000	0.000	0.000
HS-1 2.8	4	0	7.500	2.380	1.190	3.788
0.3 mg/L 2.8	4	0	6.750	0.500	0.250	0.796
1.56 mg/L 2.8	4	0	11.000	0.000	0.000	0.000
3.12 mg/L 2.8	4	0	8.750	1.500	0.750	2.387
7.8 mg/L 2.8	4	0	11.000	0.000	0.000	0.000
100 mg/L BA	4	0	11.000	0.000	0.000	0.000

Column	Range	Max	Min	Median	10%	90%
HS-1	5.000	11.000	6.000	7.000	6.000	11.000
0.3 mg/L	5.000	11.000	6.000	7.000	6.000	11.000
1.56 mg/L	5.000	11.000	6.000	7.000	6.000	11.000
3.12 mg/L	0.000	11.000	11.000	11.000	11.000	11.000
7.8 mg/L	0.000	11.000	11.000	11.000	11.000	11.000
HS-1 2.8	5.000	11.000	6.000	6.500	6.000	11.000
0.3 mg/L 2.8	1.000	7.000	6.000	7.000	6.000	7.000
1.56 mg/L 2.8	0.000	11.000	11.000	11.000	11.000	11.000
3.12 mg/L 2.8	3.000	11.000	8.000	8.000	8.000	11.000
7.8 mg/L 2.8	0.000	11.000	11.000	11.000	11.000	11.000
100 mg/L BA	0.000	11.000	11.000	11.000	11.000	11.000

Column	Skewness	Kurtosis	K-S Dist.	K-S Prob.	SWilk W	SWilk Prob
HS-1	1.720	3.265	0.382	0.041	0.801	0.103
0.3 mg/L	1.720	3.265	0.382	0.041	0.801	0.103
1.56 mg/L	1.720	3.265	0.382	0.041	0.801	0.103
3.12 mg/L	0.000	-6.000	0.000	<0.001	0.000	<0.001
7.8 mg/L	0.000	-6.000	0.000	<0.001	0.000	<0.001
HS-1 2.8	1.779	3.135	0.333	0.127	0.763	0.051
0.3 mg/L 2.8	-2.000	4.000	0.441	0.006	0.63	0.001
1.56 mg/L 2.8	0.000	-6.000	0.000	<0.001	0.000	<0.001
3.12 mg/L 2.8	2.000	4.000	0.441	0.006	0.630	0.001
7.8 mg/L 2.8	0.000	-6.000	0.000	<0.001	0.000	<0.001
100 mg/L BA	0.000	-6.000	0.000	<0.001	0.000	<0.001

Column	Sum	Sum of Squares
HS-1	31.000	255.000
0.3 mg/L	31.000	255.000
1.56 mg/L	31.000	255.000
3.12 mg/L	44.000	484.000
7.8 mg/L	44.000	484.000
HS-1 2.8	30.000	242.000
0.3 mg/L 2.8	27.000	183.000
1.56 mg/L 2.8	44.000	484.000
3.12 mg/L 2.8	35.000	313.000
7.8 mg/L 2.8	44.000	484.000
100 mg/L BA	44.000	484.000

t-test Tuesday, November 14, 2017, 4:20:02 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed ($P < 0.050$)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:20:02 PM

Data source: ET30 in 00420_Stats.JNB

Group	N	Missing	Median	10%	90%
HS-1	4	0	7.000	6.000	11.000
HS-1 2.8	4	0	6.500	6.000	11.000

Mann-Whitney U Statistic= 6.500

T = 19.500 n(small)= 4 n(big)= 4 P(est.)= 0.760 P(exact)= 0.686

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($P = 0.686$)

t-test Tuesday, November 14, 2017, 4:20:14 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Passed (P = 0.051)

Equal Variance Test: Passed (P = 0.346)

Group Name	N	Missing	Mean	Std Dev	SEM
0.3 mg/L	4	0	7.750	2.217	1.109
0.3 mg/L 2.8	4	0	6.750	0.500	0.250

Difference 1.000

t = 0.880 with 6 degrees of freedom. (P = 0.413)

95 percent confidence interval for difference of means: -1.781 to 3.781

The difference in the mean values of the two groups is not great enough to reject the possibility that the difference is due to random sampling variability. There is not a statistically significant difference between the input groups (P = 0.413).

Power of performed test with alpha = 0.050: 0.050

The power of the performed test (0.050) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.

t-test Tuesday, November 14, 2017, 4:20:26 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:20:26 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
1.56 mg/L	4	0	7.000	6.000	11.000
1.56 mg/L 2.8	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.114)

t-test Tuesday, November 14, 2017, 4:20:39 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed ($P < 0.050$)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:20:39 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
3.12 mg/L	4	0	11.000	11.000	11.000
3.12 mg/L 2.8	4	0	8.000	8.000	11.000

Mann-Whitney U Statistic= 2.000

T = 24.000 n(small)= 4 n(big)= 4 P(est.)= 0.060 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($P = 0.114$)

t-test Tuesday, November 14, 2017, 4:20:51 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:20:51 PM

Data source: ET30 in 00420_Stats.JNB

Group	N	Missing	Median	10%	90%
7.8 mg/L	4	0	11.000	11.000	11.000
7.8 mg/L 2.8	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 8.000

T = 18.000 n(small)= 4 n(big)= 4 P(est.)= 1.000 P(exact)= 1.000

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

t-test Tuesday, November 14, 2017, 4:21:04 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed ($P < 0.050$)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Tuesday, November 14, 2017, 4:21:04 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1	4	0	7.000	6.000	11.000
100 mg/L BA	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($P = 0.114$)

t-test Friday, November 17, 2017, 1:53:49 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:53:49 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1	4	0	7.000	6.000	11.000
0.3 mg/L	4	0	7.000	6.000	11.000

Mann-Whitney U Statistic= 8.000

T = 18.000 n(small)= 4 n(big)= 4 P(est.)= 0.876 P(exact)= 1.000

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

t-test Friday, November 17, 2017, 1:54:39 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:54:39 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1	4	0	7.000	6.000	11.000
1.56 mg/L	4	0	7.000	6.000	11.000

Mann-Whitney U Statistic= 8.000

T = 18.000 n(small)= 4 n(big)= 4 P(est.)= 0.876 P(exact)= 1.000

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 1.000)

t-test Friday, November 17, 2017, 1:55:09 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:55:09 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1	4	0	7.000	6.000	11.000
3.12 mg/L	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.114)

t-test Friday, November 17, 2017, 1:55:42 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed $(P < 0.050)$

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:55:42 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1	4	0	7.000	6.000	11.000
7.8 mg/L	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference $(P = 0.114)$

t-test Friday, November 17, 2017, 1:56:18 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:56:18 PM

Data source: ET30 in 00420_Stats.JNB

Group	N	Missing	Median	10%	90%
HS-1 2.8	4	0	6.500	6.000	11.000
0.3 mg/L 2.8	4	0	7.000	6.000	7.000

Mann-Whitney U Statistic= 7.500

T = 17.500 n(small)= 4 n(big)= 4 P(est.)= 1.000 P(exact)= 0.886

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.886)

t-test Friday, November 17, 2017, 1:56:47 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed ($P < 0.050$)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:56:47 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1 2.8	4	0	6.500	6.000	11.000
1.56 mg/L 2.8	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference ($P = 0.114$)

t-test Friday, November 17, 2017, 1:57:18 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:57:18 PM

Data source: ET30 in 00420_Stats.JNB

Group	**N**	**Missing**	**Median**	**10%**	**90%**
HS-1 2.8	4	0	6.500	6.000	11.000
3.12 mg/L 2.8	4	0	8.000	8.000	11.000

Mann-Whitney U Statistic= 3.500

T = 13.500 n(small)= 4 n(big)= 4 P(est.)= 0.231 P(exact)= 0.200

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.200)

t-test Friday, November 17, 2017, 1:57:56 PM

Data source: ET30 in 00420_Stats.JNB

Normality Test (Shapiro-Wilk) Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test Friday, November 17, 2017, 1:57:56 PM

Data source: ET30 in 00420_Stats.JNB

Group	N	Missing	Median	10%	90%
HS-1 2.8	4	0	6.500	6.000	11.000
7.8 mg/L 2.8	4	0	11.000	11.000	11.000

Mann-Whitney U Statistic= 2.000

T = 12.000 n(small)= 4 n(big)= 4 P(est.)= 0.067 P(exact)= 0.114

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.114)

Appendix B. Fort et al. (2017)

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TOXICITY OF SULFIDE TO EARLY LIFE STAGES OF WILD RICE (*ZIZANIA PALUSTRIS*)

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Abstract: The sensitivity of wild rice (*Zizania palustris*) to sulfide is not well understood. Because sulfate in surface waters is reduced to sulfide by anaerobic bacteria in sediments and historical information indicated that 10 mg/L sulfate in Minnesota (USA) surface water reduced *Z. palustris* abundance, the Minnesota Pollution Control Agency established 10 mg/L sulfate as a water quality criterion in 1973. A 21-d daily-renewal hydroponic study was conducted to evaluate sulfide toxicity to wild rice and the potential mitigation of sulfide toxicity by iron (Fe). The hydroponic design used hypoxic test media for seed and root exposure and aerobic headspace for the vegetative portion of the plant. Test concentrations were 0.3, 1.6, 3.1, 7.8, and 12.5 mg/L sulfide in test media with 0.8, 2.8, and 10.8 mg/L total Fe used to evaluate the impact of iron on sulfide toxicity. Visual assessments (i.e., no plants harvested) of seed activation, mesocotyl emergence, seedling survival, and phytoxicity were conducted 10 d after dark-phase exposure. Each treatment was also evaluated for time to 30% emergence (ET30), total plant biomass, root and shoot lengths, and signs of phytotoxicity at study conclusion (21 d). The results indicate that exposure of developing wild rice to sulfide at $\geq$3.1 mg sulfide/L in the presence of 0.8 mg/L Fe reduced mesocotyl emergence. Sulfide toxicity was mitigated by the addition of Fe at 2.8 mg/L and 10.8 mg/L relative to the control value of 0.8 mg Fe/L, demonstrating the importance of iron in mitigating sulfide toxicity to wild rice. Ultimately, determination of site-specific sulfate criteria taking into account factors that alter toxicity, including sediment Fe and organic carbon, are necessary. *Environ Toxicol Chem* 2017;36:2217–2226. © 2017 SETAC

Keywords: Wild rice Sulfide Toxicity Iron Hydroponics

INTRODUCTION

Historically, the impacts of sulfate, and thus sulfide, toxicity to wild rice (*Zizania palustris L.*) in Minnesota (USA) have been addressed by using the surface water sulfate water quality standard of 10 mg/L established by the Minnesota Pollution Control Agency [1,2]. To address the practicality of this standard, an initial 21-d hydroponic study was previously performed [3] to determine the toxicity of sulfate to wild rice seeds and seedlings. The results suggested that sulfate does not adversely affect germination and early development of wild rice at concentrations <5000 mg/L over a 21-d hydroponic exposure period. Some effects found at high sulfate concentrations were also observed in osmotically equivalent chloride treatments, and some sulfate-specific stimulatory effects may be attributable to the effects of sulfate as a plant nutrient. Two endpoints, shoot length and leaf number, appeared to have sulfate-specific toxic responses; however, the remainder of the observed responses were likely the result of a general conductivity-induced stress and not specifically the result of sulfate. Root length appeared to be an especially sensitive endpoint to conductivity-related stress induced by chloride-dominated salt solutions [3].

Sulfate in surface waters is reduced to sulfide by anaerobic bacteria in sediments, and sulfide is known to be much more toxic to aquatic organisms than sulfate. As an extension of the original hydroponics study [3], which examined sulfate toxicity to developing wild rice, sulfide toxicity to early life stage wild rice was evaluated under varying iron (Fe) concentrations representative of those known to be present in sediment porewaters in Minnesota. The sulfide toxicity threshold under varying Fe concentrations was determined, to facilitate a better understanding of the role of Fe in altering sulfide toxicity. The primary objective of the present study was to determine the toxicity of sulfide to wild rice seeds and seedlings from the State of Minnesota. Preliminary studies were conducted to determine the most appropriate culture media and test conditions, identify sensitive test endpoints, establish a statistically valid experimental design, and determine appropriate sulfide exposure concentrations for the range of wild rice response endpoints selected. These findings will be used to further understand the possible impact of sulfate released into the environment and subsequently reduced to sulfide under varying sediment conditions, and support the efforts to re-evaluate the State of Minnesota's wild rice sulfate water quality standard of 10 mg/L [2]. Concentration–response data, including 25% inhibitory concentrations (IC25) values, and no- and lowest-observed-effect concentrations (NOEC and LOEC) for the effects of sulfide on wild rice were determined.

MATERIALS AND METHODS

Preliminary studies

Preliminary range-finding studies were conducted to establish the testing conditions necessary to maintain a hydroponic exposure to sulfide, and to determine appropriate sulfide and Fe concentrations for the definitive study. A daily-renewal hydroponic system utilizing a modified Hoagland's solution (HS-1; [4,5]) was used to test the effects of sulfide on 10

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biological endpoints in wild rice seeds and seedlings over 21 d. A summary of the experimental design and conditions is provided in Table 1.

Hydroponic media and test materials

Modified HS-1 solution [4] contained 25% ammonium (molar basis) in a mixture of ammonium and nitrate [3], and served as the base medium and diluent for all test exposures in the definitive study. Deionized water was used to prepare all solutions, and was routinely tested to ensure the absence of various organic and inorganic contaminants. The modified HS-1 macronutrients consisted of 2.55 mM NO_3^-, 0.92 mM NH_4^+, 0.12 mM $H_2PO_4^-$, 1.10 mM K^+, and 0.75 mM Ca^{2+}, 0.50 mM Mg^{2+}, and 0.50 mM SO_4^{2-}. Micronutrients included 46.3 μM boron (B), 14.9 μM Fe, 0.76 μM zinc, 0.31 μM copper, 9 μM manganese, and 0.50 μM molybdenum. The sulfide toxicity threshold under varying iron concentrations was determined, to facilitate a better understanding of the role of iron in altering sulfide toxicity. All salts were reagent-grade materials obtained from SigmaAldrich (St. Louis, MO; >98% pure). Hydrated sodium sulfide ($Na_2S \cdot 9\ H_2O$, 99.99% pure, Sigma-Aldrich) and ferric chloride ($FeCl_3$, 98.00%, Merck) were used throughout the present study. The sulfide and Fe treatments are identified in Table 1. In addition to the HS-1 (1:4 ammonium:nitrate) negative control (0.8 mg Fe/L), and HS-1 controls containing additional iron (2.8 mg and 10.8 mg Fe/L), a 100-mg boron (B)/L treatment in HS-1 (1:4) media was included as a positive control toxicant. Boron was selected as a positive control based on use in the initial hydroponic study evaluating the toxicity of sulfate and chloride [3].

Wild rice seeds

Wild rice seeds were hand-harvested from Little Round Lake in Becker County, Minnesota (USA; 46°58′13.32″N and 95°44′44.49″W), sieved through a 4-mm mesh, and then sieved through a 2-mm mesh to remove debris. Seeds were stored at 4 °C in the dark prior to test initiation. The percentage of emergence at day 21 in preliminary studies was 47.5%, and was thus considered acceptable for use based on both preliminary studies and Fort et al. [3], as a relatively modest proportion of *Zizania palustris* germinate (criteria set at ≥30%).

Exposure system

Based on the results of preliminary testing, a sulfide exposure series of 0.3, 1.6, 3.1, 7.8, and 12.5 mg/L sulfide was utilized. Test solutions were provided using a static-renewal design in 10-L hydroponic tanks. The hydroponic tanks were plastic aquaria (~35 cm × 20 cm × 15 cm deep). Each tank was equipped with 1-L baskets with inert mesh to support the seeds and seedlings. One-liter baskets to house seeds and seedlings evaluated on day 10 (visual assessments only) and day 21 (study termination, all endpoints) were placed in each of the 4 replicate tanks per treatment or control. Exposure media were replaced daily using a 70% renewal rate. Treatment tanks were randomly assigned to a position in the exposure system to account for possible variations in temperature and light intensity. Seeds selected for study were

Table 1. Experimental conditions for hydroponic evaluation of sulfide toxicity and impact of iron in *Zizania palustris*

Test substance	Sulfide (suspected toxicant) and iron (suspected to interact with sulfide)
Test concentrations	Sulfide series: <0.1 (control), 0.3, 1.6, 3.1, 7.8, 12.5 mg/L. Each sulfide series run with either 0.8, 2.8, or 10.8 mg/L Fe
Test system (species)	*Zizania palustris* (wild rice)
Initial stage	Seed, September 8, 2014 seed lot from Little Round Lake (03-0302-00)
Exposure period	10-d (mesocotyl emergence phase in dark) and 21-d (free leaf phase). Total exposure period 21 d
Selection criteria	Seed uniformity, visual quality, and activation
Exposure system	Static-renewal (daily) in controlled environmental chambers under anaerobic aquatic phase and aerobic vegetative (shoot) phase
Exposure route	Water (hydroponics)
Test vessel	10-L chamber with 1-L sub-basket equipped with mesh bottom supports for seeds
Exchange frequency	Daily, 0.7 volumes/d
Water source	Deionized water
Media	HS-1[a] modified with 1:4 ammonia:nitrate
Replication	4/treatment
Seed density	80 seeds/replicate (320 seeds/ treatment or control)
Vessel placement	Tanks are placed randomly throughout the experimental area
Positive control	Boric acid (100 mg B/L)
Test performance criteria (control)	See Table 6
Test endpoints	
Daily	Activation, mesocotyl emergence, seedling survival, and visual inspection of development (emergence and normalcy of development)
SD 10	Activation, mesocotyl emergence (%), survival, leaf number, and signs of phytotoxicity
Conclusion (SD 21)	Activation, mesocotyl emergence (%, time to 30% emergence [ET30] if possible), survival, shoot and seminal root length and weight, leaf number, second and free leaf biomass, and signs of phytotoxicity
Feeding	
Nutrient/micronutrients	HS-1 modified with 1:4 ammonia:nitrate and either 0.8, 2.8, or 10.8 mg Fe/L
Frequency	Daily, 0.7 volumes renewed
Lighting	
Photoperiod	Dark through SD 10, then 16-h light:8-h dark
Intensity (post SD 10)	5000 ± 1000 lux (measured daily at water surface)
Temperature	In all replicates, daily, 21 ± 2 °C (day), and nightly, 12 °C ± 2 °C (night)
pH, ORP, DO, and sulfide	2×/d in all replicates prior to and following renewal
Conductivity, alkalinity, hardness, ammonia, total Fe, nitrate, sulfate, phosphate, total residual oxidants	Initiation (SD 0), SD 7, SD 14, and SD 21 (conclusion) of study in a representative test replicate of each treatment

[a]Modified Hoaglund's solution.
ORP = oxidation-reduction potential; DO = dissolved oxygen; SD = standard deviation; HS-1 = Hoagland's solution.

randomly placed in each basket such that 5 seeds were added to each insert basket in accordance with a randomized design chart until each basket contained 80 seeds/replicate (320 total per exposure condition), which was adequate to evaluate concentration–response relationships and assess significant differences in the treatments relative to their respective control (i.e., the HS-1 medium with a given Fe concentration and no sulfide). For the first 10 d of the present study, the seeds were kept in the dark to promote mesocotyl emergence and development. Following the 10-d dark-phase germination and development phase, a combination of incandescent and fluorescent plant growlights was used to provide a 16:8-h light:dark photoperiod at an intensity of 5000 ± 1000 lux (lumens/m^2) at the surface of the culture media and plants.

Water temperature was maintained at $21 \pm 2\,^{\circ}C$ (day) and $12 \pm 2\,^{\circ}C$ (night). Test solution pH was maintained between 6.0 and 7.5 s.u. in all exposures. Within a given replicate, variation in pH was ± 0.5 s.u. for each daily measurement at time 0 (renewal) and time 24 (immediately prior to subsequent renewal), and over the course of the study. This pH range is well within the range of conditions where wild rice grows naturally. Hypoxic (dissolved oxygen < 2.0 mg/L) conditions were maintained within the hydroponic tanks; the HS-1 test medium was deoxygenated with N_2 gas, stored in a sealed carboy until use, and checked for oxygen concentration immediately prior to use. Each hydroponic tank was equipped with a 6-inch, small-bubble air stone to deliver a constant flow of N_2 gas to the tank and ensure hypoxic conditions were maintained. For hypoxic root growth and aerobic vegetative growth, the basket was placed in the hydroponic aquaria such that the seeds resided in the culture media approximately 1 cm below the air:media interface. Seeds germinated under hypoxic conditions and mesocotyls developed in aerobic conditions under this design. Plastic wire mesh was placed inside the aquaria to provide a trellis to support vegetative growth above the hypoxic culture media. Sulfide-treated test solutions were prepared daily for use in renewal. Sulfide concentrations in the test solutions were measured prior to and following each daily media renewal using an ion-selective probe. Sulfide stability in the culture media was aided by the N_2 gas balance. A summary of the present study conditions is provided in Table 1.

Water quality analyses

In each replicate tank, temperature and light intensity (lux) were measured daily throughout the 21-d study. The dissolved oxygen (aqueous and headspace; US Environmental Protection Agency [USEPA] method 360.1 [6]), pH, oxidation-reduction potential, and sulfide were measured twice daily (i.e., prior to and following solution renewal). The dissolved oxygen, oxidation-reduction potential, and sulfide (USEPA method 9215 [7]) measurements were conducted at the same water depth as seed exposure. In addition, specific conductance (conductivity; USEPA method 120.1 [8]), total hardness (USEPA method 130.2 [9]), total alkalinity (USEPA method 310.1 [10]), total iron (USEPA method 8008 [11]), total residual oxidants (USEPA method 330.5 [12]), ammonia-nitrogen (USEPA method 350.2 [13]), sulfate (USEPA method 375.4 [14]), nitrate (USEPA method 353.2 [15]), and phosphate (USEPA method 365.2 [16]) were measured in the media in a replicate of each treatment on days 0, 7, 14, and 21 (conclusion) of the study [17]. Time-weighted average sulfide concentrations were calculated in accordance with methods of the Organisation for Economic Co-operation and Development, and accounted for the variation in instantaneous concentration over time so that the area under the time-weighted average is equal to the area under the concentration curve [18].

Data collection and biological endpoints

Visual assessments only (i.e., no plants harvested) of the following endpoints (Table 2) were conducted on day 10 following dark-phase exposure to evaluate: activation (germination), mesocotyl emergence, time to emergence (expressed as the time to 30% emergence [ET30]), seedling survival, free leaf number, and abnormal development including chlorosis (phytotoxicity). Signs of chlorosis and stem or root rot were based on observation using a dissecting microscope as needed. The use of an ET30 was based on previous studies [3] of wild rice emergence revealing that in normal-appearing seeds, between 30% and 60% of mesocotyls emerged over the course of a trial. The mesocotyl emergence acceptance frequency was set at 30% in the previous study with sulfate [3] and the present study. All subbaskets were evaluated for the endpoints mentioned, as well as the following 5 endpoints at study conclusion (day 21): shoot (mesocotyl, coleoptiles, and primary leaf) weight, shoot (mesocotyl, coleoptiles, and primary leaf) length, root (seminal and rootlets) weight, seminal root length, and free leaf biomass. All weights were expressed as dry weight recorded to the nearest 0.1 mg by drying the individual parts of each seedling together in an aluminum pan in an oven at $105\,^{\circ}C$ for 24 h.

Data analysis

The experimental unit was the replicate and $\alpha = 0.05$. For measurement endpoints (i.e., weights and lengths), replicate level data were based on the mean value for all plants measured in that replicate with the exception of the ET30 data sets, which were based on median values. The statistical tests used to compare the culture media with the sulfide and B positive control differed depending on the data type and distribution for each measurement endpoint. No outliers were identified (Grubbs's test). Data that were expressed as a percentage or proportion were transformed using the arcsine square root before further analysis. No other transformations were used. The IC25 and 95% confidence intervals for appropriate endpoints were determined by linear interpolation. Normal distribution (Shapiro–Wilks' test, $\alpha = 0.05$) and equivalence of variances (Levene's test, $\alpha = 0.05$) were performed to determine parametric data sets. For measurement endpoints, comparisons between the treatments and designated controls were performed using one-way analysis of variance (ANOVA) or a nonparametric equivalent (Kruskal–Wallis ANOVA). In all cases, sulfide treatments sharing the same Fe concentration were compared against a control condition containing that same iron concentration. When the initial test was statistically significant, post hoc tests were performed, including the Bonferroni *t* test for parametric test and Dunn's nonparametric test. Treatment median ET30 values were determined by deriving the median of replicate ET 30 values. The ET30 values for each treatment were compared with their respective controls using a Mann–Whitney *U* test.

RESULTS

Exposure conditions and sulfide concentrations

Exposure solution pH was maintained at 6.0 to 7.5 s.u. in all replicates of controls and treatments and was ± 0.5 s.u. within a given replicate for each daily measurement. The dissolved oxygen concentrations were maintained at <2.0 mg/L in all

Table 2. Effects of sulfide on hydroponic development and growth of *Zizania palustris* endpoints following 10-d exposure

Treatment		Response[a]				
Sulfide[b] (mg/L)	Iron (mg/L)	Seed activation (%)	Mesocotyl emergence (%)	Seedling survival (%)	Mean free leaf (no.)	Abnormal appearance (%)
<0.01 (negative control)	0.8[c]	100.0 (0.0)	29.1 (0.46)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
<0.01 (positive control)[d]	0.8	100.0 (0.0)	8.4[e] (0.66)	100.0 (0.0)	0.0 (0.0)	100[f](0.0)
0.3	0.8	100.0 (0.0)	28.8 (0.47)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
1.6	0.8	100.0 (0.0)	27.8 (0.74)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
3.1	0.8	100.0 (0.0)	24.1 (0.46)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
7.8	0.8	100.0 (0.0)	14.4[g] (0.63)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
12.5	0.8	100.0 (0.0)	0.0[g] (0.00)	– (–)	– (–)	– (–)
<0.01 (negative control)	2.8	100.0 (0.0)	28.1 (0.63)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
0.3	2.8	100.0 (0.0)	27.5 (0.67)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
1.6	2.8	100.0 (0.0)	26.9 (0.63)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
3.1	2.8	100.0 (0.0)	25.0 (0.47)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
7.8	2.8	100.0 (0.0)	15.6[h] (0.63)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
12.5	2.8	100.0 (0.0)	0.0[h] (0.00)	– (–)	– (–)	– (–)
<0.01 (negative control)	10.8	100.0 (0.0)	28.8 (0.67)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
0.3	10.8	100.0 (0.0)	29.1 (0.46)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
1.6	10.8	100.0 (0.0)	27.2 (0.74)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
3.1	10.8	100.0 (0.0)	26.9 (0.63)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
7.8	10.8	100.0 (0.0)	22.2[i] (1.00)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)
12.5	10.8	100.0 (0.0)	13.8[i] (0.47)	100.0 (0.0)	0.0 (0.0)	0.0 (0.0)

[a]Mean with standard error of the mean below. Mean of 4 replicates/treatment with 80 seeds/replicate (320 seeds/treatment).
[b]Nominal sulfide concentration.
[c]HS-1 contains 0.8 mg Fe/L. Statistical comparisons made with HS-1 with 0.8, 2.8, or 10.8 mg Fe/L controls depending on treatment set analyzed to hold the nominal Fe constant during analysis.
[d]100 mg/L boric acid (positive control).
[e]Significantly less than HS-1 with 0.8 mg Fe/L, *t* test, $p < 0.001$.
[f]Significantly greater than HS-1 with 0.8 mg Fe/L, *t* test, $p < 0.001$.
[g]Significantly less than HS-1 with 0.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[h]Significantly less than HS-1 with 2.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[i]Significantly less than HS-1 with 10.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
HS-1 = Hoagland's solution.

treatments, and hydroponic chamber temperatures were maintained at $21 \pm 2\,°C$ (day) and $12 \pm 2\,°C$ (night) in all replicates of controls and treatments. A summary of sulfide concentrations based on time-weighted average values measured following test solution renewal (T0) and immediately prior to renewal (T24), along with an evaluation of 24-h sulfide losses in each treatment is presented in Table 3. Inter-replicate percentage coefficient of variation (CV) within the control or a given sulfide exposure was ≤6% in pre- and post-test solution renewal samples based on time-weighted average concentrations. The interreplicate CV for 24-h sulfide loss based on the time-weighted average concentration was ≤30%. Sulfide loss between 24-h renewals ranged from 15.2 to 23.5% in the 0.8 mg Fe/L treatments, 29.9 to 55.6% in the 2.8 mg Fe/L treatments, and 87.6 to 95.4% in the 10.8 mg Fe/L treatments. The results indicate that nominal and measured sulfide concentrations in freshly prepared test solutions were very similar, but that increased Fe reduced free sulfide concentrations in a manner that was not necessarily a linear function of iron concentrations.

Control and positive control performance

The control (HS-1) seed activation, mesocotyl emergence, and seedling survival were >95%, >30%, and >90%, respectively; on study days 10 (Table 2) and 21 (Table 4), which met validity criteria previously established for hydroponic studies [3]. The HS-1 control plants were compared against those grown in a 100 mg/L B positive control known to induce phytotoxicity. The occurrence of 100% phytotoxicity indicated compliance with the pre-established test acceptability criterion of ≥80% [3]. In contrast, HS-1 plants exhibited no phytotoxicity. Decreased emergence, root length and weight, and free leaf weight, an increase in the median ET30, and phytotoxicity were observed in wild rice exposed to 100 mg B/L relative to the HS-1 control with 0.8 mg Fe/L.

Sulfide toxicity with 0.8 mg Fe/L

Study day 10. Exposure of wild rice to 7.8 and 12.5 mg/L sulfide decreased emergence relative to the HS-1 control with 0.8 mg Fe/L. Free leaf number was 0 in the control and all treatments (Table 2).

Study day 21. Decreased emergence, root length and weight, and free leaf weight, an increase in the median ET 30, and phytotoxicity were observed in wild rice exposed to 100 mg B/L relative to the HS-1 control with 0.8 mg Fe/L (Table 4). Exposure of wild rice to 3.1, 7.8, and 12.5 mg/L sulfide decreased emergence at day 21 relative to the HS-1 control with 0.8 mg Fe/L. Emergence was greater in seeds exposed to 12.5 mg/L sulfide with 10.8 mg Fe/L than in treatments with 0.8 and 2.8 mg Fe/L. Seeds exposed to 12.5 mg/L sulfide exhibited 21.3% emergence in the presence of 10.8 mg/L Fe compared with no emergence occurring in this same sulfide concentration in the 2 lower Fe conditions. Root length, shoot length, root biomass, shoot biomass, secondary leaf biomass, and leaf number were 0 in seedlings exposed to 12.5 mg/L sulfide with 0.8 mg Fe/L, as a result of no emergence. The ET30 (Table 5) generally increased with increasing sulfide concentration in the 0.8 mg/L Fe series (i.e., longer emergence times indicate toxicity), ranging from a median of 10 d in the control to >21 d in the 7.8 and 12.5 mg/L sulfide treatments. The ET30 values were significantly greater in the 7.8 and 12.5 mg/L sulfide treatments than in other sulfide treatments with these Fe treatments.

Overall, mesocotyl emergence was the most sensitive endpoint, and activation, seedling survival, and phytotoxicity

Table 3. Measured sulfide concentrations in hydroponic chambers at renewal and 24-h post renewal

Treatment	Time-weighted average[a] (mg/L)				
	Post renewal (T0)[b]	CV (%)	Pre-renewal (T24)[c]	CV (%)	Loss (%)
HS-1[d]	<0.01	–	<0.01	–	–
100 mg B/L/wild rice	<0.01	–	<0.01	–	–
0.3 mg/L Sulfide	0.34	1.1	0.26	1.3	23.5
1.6 mg/L Sulfide	1.56	0.8	1.31	3.1	16.0
3.1 mg/L Sulfide	3.29	1.5	2.53	2.9	23.1
7.8 mg/L Sulfide	7.71	0.7	6.54	5.4	15.2
12.5 mg/L Sulfide	12.52	1.5	10.52	3.8	16.0
HS-1d + 2.8 mg/L Fe	<0.01	–	<0.01	–	–
0.3 mg/L Sulfide + 2.8 mg/L Fe	0.31	2.1	0.20	1.3	35.5
1.6 mg/L Sulfide + 2.8 mg/L Fe	1.48	1.8	1.00	1.4	32.4
3.1 mg/L Sulfide + 2.8 mg/L Fe	3.20	1.3	1.42	2.0	55.6
7.8 mg/L Sulfide + 2.8 mg/L Fe	7.49	1.3	4.13	1.6	44.9
12.5 mg/L Sulfide + 2.8 mg/L Fe	11.91	1.5	8.35	0.9	29.9
HS-1[d] + 10.8 mg/L Fe	<0.01	–	<0.01	–	–
0.3 mg/L Sulfide + 10.8 mg/L Fe	0.33	1.3	0.02	0.0	93.9
1.6 mg/L Sulfide + 10.8 mg/L Fe	1.52	1.2	0.07	3.4	95.4
3.1 mg/L Sulfide + 10.8 mg/L Fe	3.21	1.1	0.31	3.6	90.3
7.8 mg/L Sulfide + 10.8 mg/L Fe	7.25	2.2	0.68	1.5	90.6
12.5 mg/L Sulfide + 10.8 mg/L Fe	11.75	1.6	1.46	3.5	87.6

[a]Analysis based on Organisation for Economic Co-operation and Development method 211 [6].
[b]Time-weighted average based on analysis of fresh test solutions. Limit of detection = 0.01 mg/L.
[c]Time-weighted average based on analysis of 24 h aged test solutions at prior to renewal of fresh test solutions.
[d]Modified Hoagland's solution.
HS-1 = Hoagland's solution; CV = coefficient of variation.

were the least sensitive endpoints. No emergence occurred in the 12.5 mg/L sulfide treatment containing 0.8 mg Fe/L.

Sulfide toxicity with 2.8 or 10.8 mg Fe/L

Study day 10. Exposure of wild rice to 7.8 or 12.5 mg/L sulfide significantly decreased emergence relative to the HS-1 control in both the 2.8 mg and 10.8 mg Fe/L treatments (Table 2). Leaf number was 0 in the controls and all treatments for both the 2.8 mg and 10.8 mg Fe/L treatments.

Study day 21. Exposure of wild rice to 7.8 or 12.5 mg/L sulfide significantly decreased emergence relative to the HS-1 control in both the 2.8 and 10.8 mg Fe/L treatments (Table 4). Evaluation of the effect of iron concentration on emergence at a given sulfide concentration indicated that the addition of 10.8 mg Fe/L significantly reduced the effects of sulfide on mesocotyl emergence in the 7.8 mg/L sulfide treatments (ANOVA, Bonferroni t test, $p < 0.001$) and 400 μM (Kruskal–Wallis–ANOVA, Dunn's test, $p < 0.05$), compared with equivalent sulfide treatments with the addition of 0.8 and 2.8 mg Fe/L. In the 2.8 mg Fe/L treatment series, the median ET30 ranged from 12 d in the control to >21 d in the 12.5 mg/L sulfide treatment (Table 6). The ET30 values were significantly greater in the 7.8 and 12.5 mg/L sulfide treatments than in other sulfide treatments with these iron treatments. In terms of plants exposed to 10.8 mg Fe/L (Table 6), the median ET30 ranged from 10 d in the control to >21 d in the 12.5 mg/L sulfide treatment. The ET30 values generally increased with increasing sulfide concentrations for these iron concentrations, and the median ET30 values for 7.8 and 12.5 mg/L sulfide were significantly greater than in other sulfide treatments (Mann–Whitney U test, $p \leq 0.005$; Table 5). In addition, the ET30 decreased in the 3.1 mg/L sulfide treatment with increasing Fe concentration (Mann–Whitney U test, $p \leq 0.05$). Root length, shoot length, root biomass, shoot biomass, secondary leaf biomass, and leaf number were all 0 in seedlings exposed to 12.5 mg/L sulfide with 2.8 mg Fe/L (Table 4). This was because of the lack of emergence in the 12.5 mg/L sulfide with 2.8 mg Fe/L treatment. However, these effects were not observed in the presence of 10.8 mg Fe/L.

Overall, mesocotyl emergence was the most sensitive endpoint, whereas activation, seedling survival, and phytotoxicity were the least sensitive endpoints. No emergence occurred at 12.5 mg/L sulfide in the presence of 2.8 mg Fe/L. Mesocotyl emergence, seedling growth, and survival were recorded at 12.5 mg/L sulfide with 10.8 mg Fe/L. Thus, emergence and all root and shoot measures were greater in seeds germinated and grown in the presence of 12.5 mg/L sulfide and 10.8 mg Fe/L than in those exposed to the same amount of sulfide with either 0.8 or 2.8 mg Fe/L. The formation of a fine layer of black plaque was detected on the seminal roots of rice seedlings exposed to 7.8 mg/L sulfide with 2.8 or 10.8 mg/L Fe and 12.5 mg/L sulfide with 10.8 mg/L Fe (Figure 1). The layer of plaque when removed did not produce sufficient material to analyze or investigate further. Sulfide NOEC, LOEC, chronic values (the geometric mean of the NOEC and LOEC values), and IC25 values for each Fe concentration on day 10 and day 21 are presented in Table 6.

DISCUSSION

Mesocotyl emergence was the most sensitive endpoint at sulfide concentrations $\geq$3.1 mg/L with 0.8 mg/L Fe and an IC25 value of 3.9 (3.5–4.3) mg/L sulfide. However, exposure of developing wild rice to sulfide concentrations $\geq$7.8 mg/L (with additions of 2.8 mg and 10.8 mg Fe/L and IC25 values of 7.1 [6.5–7.7] and 9.3 [8.8–9.8] mg/L, respectively) was required to significantly reduce mesocotyl emergence. Furthermore, addition of 10.8 mg/L Fe resulted in reduction of sulfide toxicity compared with lower Fe concentration treatments, based on emergence, changes in median ET30 values, and greater percentage of emergence in seeds exposed to 12.5 mg/L sulfide.

Seed activation, seedling survival, and phytotoxicity were the least sensitive endpoints. Root and shoot growth endpoints were less sensitive than emergence endpoints. The day-21 sulfide chronic values in the 0.8 mg Fe/L series ranged from 2.2 mg/L sulfide for emergence to >12.5 mg/L sulfide for

Table 4. Effects of sulfide on hydroponic development and growth of *Zizania palustris* endpoints after 21-d exposure

Treatment		Response[a]									
Sulfide[b] (mg/L)	Iron (mg/L)	Seed activation (%)	Mesocotyl emergence (%)	Seedling survival (%)	Mean seminal root biomass (g, dry wt)	Mean seminal root length (cm)	Mean shoot biomass (g, dry wt)	Mean shoot length (cm)	Mean 2° leaf biomass (g, dry wt)	Mean free leaf (no.)	Abnormal appearance (%)
<0.01 (negative control)	0.8[c]	100.0 (0.0)	44.1 (0.46)	100.0 (0.0)	0.0016 (0.0002)	6.588 (0.301)	0.0044 (0.0003)	2.567 (0.123)	0.0088 (0.0007)	2.8 (0.2)	0.0 (0.0)
<0.01 (positive control)[d]	0.8	100.0 (0.0)	8.8[e] (0.47)	100.0 (0.0)	0.0010[f] (0.0001)	3.566[f] (0.218)	0.0039 (0.0004)	2.330 (0.150)	0.0057[g] (0.0010)	2.5 (0.4)	100[h] (0.0)
0.3	0.8	100.0 (0.0)	43.1 (0.41)	100.0 (0.0)	0.0016 (0.0001)	6.012 (0.229)	0.0038 (0.0002)	2.456 (0.116)	0.0084 (0.0011)	2.7 (0.3)	0.0 (0.0)
1.6	0.8	100.0 (0.0)	41.6 (0.66)	100.0 (0.0)	0.0020 (0.0002)	5.453 (0.238)	0.0035 (0.0002)	2.309 (0.076)	0.0068 (0.0006)	3.0 (0.2)	0.0 (0.0)
3.1	0.8	100.0 (0.0)	36.6[i] (0.66)	100.0 (0.0)	0.0016 (0.0002)	5.434 (0.345)	0.0038 (0.0002)	2.468 (0.092)	0.0075 (0.0009)	2.8 (0.1)	0.0 (0.0)
7.8	0.8	100.0 (0.0)	24.4[i] (0.41)	100.0 (0.0)	0.0014 (0.0002)	4.915 (0.386)	0.0040 (0.0003)	2.840 (0.098)	0.0081 (0.0009)	3.6 (0.3)	0.0 (0.0)
12.5	0.8	100.0 (0.0)	0.0[i] (0.00)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
<0.01 (negative control)	2.8	100.0 (0.0)	45.0 (0.67)	100.0 (0.0)	0.0016 (0.0001)	4.790 (0.155)	0.0042 (0.0003)	2.511 (0.078)	0.0073 (0.0008)	3.2 (0.2)	0.0 (0.0)
0.3	2.8	100.0 (0.0)	43.4 (0.46)	100.0 (0.0)	0.0019 (0.0002)	5.315 (0.283)	0.0041 (0.0004)	2.531 (0.075)	0.0069 (0.0009)	3.1 (0.2)	0.0 (0.0)
1.6	2.8	100.0 (0.0)	40.9 (0.46)	100.0 (0.0)	0.0017 (0.0001)	5.890 (0.427)	0.0043 (0.0004)	2.571 (0.136)	0.0074 (0.0009)	3.7 (0.2)	0.0 (0.0)
3.1	2.8	100.0 (0.0)	40.0 (0.67)	100.0 (0.0)	0.0014 (0.0001)	5.506 (0.290)	0.0038 (0.0002)	2.615 (0.125)	0.0066 (0.0008)	3.1 (0.2)	0.0 (0.0)
7.8	2.8	100.0 (0.0)	32.8[j] (0.57)	100.0 (0.0)	0.0013 (0.0001)	5.127 (0.403)	0.0035 (0.0005)	2.331 (0.131)	0.0066 (0.0010)	2.6 (0.3)	0.0 (0.0)
12.5	2.8	100.0 (0.0)	0.0[k] (0.00)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
<0.01 (negative control)	0.8	100.0 (0.0)	46.3 (0.47)	100.0 (0.0)	0.0016 (0.0001)	5.356 (0.299)	0.0035 (0.0002)	2.431 (0.112)	0.0072 (0.0009)	2.9 (0.2)	0.0 (0.0)
0.3	10.8	100.0 (0.0)	45.9 (0.46)	100.0 (0.0)	0.0012 (0.0001)	5.120 (0.285)	0.0034 (0.0001)	2.293 (0.124)	0.0073 (0.0005)	2.5 (0.2)	0.0 (0.0)
1.6	10.8	100.0 (0.0)	43.4 (0.66)	100.0 (0.0)	0.0014 (0.0001)	4.576 (0.221)	0.0032 (0.0002)	1.962 (0.071)	0.0061 (0.0006)	2.8 (0.3)	0.0 (0.0)
3.1	10.8	100.0 (0.0)	45.6 (0.63)	100.0 (0.0)	0.0015 (0.0001)	5.402 (0.078)	0.0041 (0.0002)	2.784 (0.080)	0.0082 (0.0004)	3.3 (0.2)	0.0 (0.0)
7.8	10.8	100.0 (0.0)	41.9[l] (0.63)	100.0 (0.0)	0.0015 (0.0001)	4.640 (0.287)	0.0038 (0.0002)	2.542 (0.065)	0.0078 (0.0005)	2.9 (0.1)	0.0 (0.0)
12.5	10.8	100.0 (0.0)	21.3[m] (0.67)	100.0 (0.0)	0.0014 (0.0001)	5.522 (0.288)	0.0038 (0.0003)	2.776 (0.120)	0.0091 (0.0007)	3.3 (0.1)	0.0 (0.0)

[a] Mean with standard error of the mean below. Mean of 4 replicates/treatment with 80 seeds/replicate (320 seeds/treatment).
[b] Nominal sulfide concentration.
[c] HS-1 contains 0.8 mg Fe/L. Statistical comparisons made without HS-1 with 0.8, 2.8, or 10.8 mg Fe/L controls depending on treatment set analyzed to hold the nominal Fe constant during analysis.
[d] 100 mg/L boric acid (positive control).
[e] Significantly less than HS-1 with 0.8 mg Fe/L, *t* test, $p < 0.001$.
[f] Significantly less than HS-1 with 0.8 mg Fe/L, *t* test, $p = 0.005$.
[g] Significantly less than HS-1 with 0.8 mg Fe/L, *t* test, $p = 0.025$.
[h] Significantly greater than HS-1 with 0.8 mg Fe/L, *t* test, $p < 0.001$.
[i] Significantly less than HS-1 with 0.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[j] Significantly less than HS-1 with 2.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[k] Significantly less than HS-1 with 2.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[l] Significantly less than HS-1 with 10.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
[m] Significantly less than HS-1 with 10.8 mg Fe/L, Kruskal–Wallis-analysis of variance, Dunn's test, $p < 0.05$.
HS-1 = Hoagland's solution.

seed activation, survival, and phytotoxicity endpoints. The sulfide chronic values for replicates exposed to 2.8 mg and 10.8 mg Fe/L ranged from 4.9 mg/L sulfide for emergence to >12.5 mg/L sulfide for seed activation, survival, and phytotoxicity endpoints, providing evidence of a trend toward decreased sulfide toxicity with increased Fe concentration. Historical studies of sulfide toxicity were reviewed by Lamers et al. [19]. Although no studies with wild rice were included, studies with *Oryza sativa* (Asian rice) in hydroponic culture showed reduced productivity at 5 mg/L sulfide [20] and 0.9 mg/L sulfide [21], and radial oxygen loss and reduced at nutrient uptake at 0.3 to 1.9 mg/L sulfide [22]. More recently, Pastor et al. [23] demonstrated sulfide toxicity to wild rice at 0.3 mg/L sulfide, which was markedly less than that found in the present study.

Table 5. Median emergence time endpoint in wild rice exposed to sulfide in the presence of iron on day 21[a]

	Median emergence time (d)						
Treatment iron (mg/L)	HS-1[b]	100 mg/L BA[c]	0.3 mg/L S^{2-}	1.6 mg/L S^{2-}	3.1 mg/L S^{2-}	7.8 mg/L S^{2-}	12.5 mg/L S^{2-}
0.8	10	>21[d]	11	12	15	>21[d]	>21[d]
2.8	12	–	12	12	12[e]	19[f]	>21[d]
10.8	10	–	10	12	12[e]	15[g]	>21[b]

[a]Based on time (in days) required to achieve 30% emergence.
[b]Negative control.
[c]Boric acid, positive control.
[d]Significantly greater than HS-1with 0.8 mg Fe/L, Mann–Whitney U test, $p < 0.001$.
[e]Significantly less than 3.1 mg/L sulfide with 0.8 mg Fe/L, Mann–Whitney U test, $p \leq 0.05$.
[f]Significantly greater than HS-1with 2.8 mg Fe/L, Mann–Whitney U test, $p = 0.005$.
[g]Significantly greater than HS-1with 10.8 mg Fe/L Mann–Whitney U test, $p = 0.001$.
BA = boric acid; HS-1 = Hoagland's solution.

Table 6. Summary of numerical endpoints determined on days 10 and 21[a]

	Day 10				Day 21			
Endpoint	NOEC[b] (mg/L S^{2-})	LOEC[c] (mg/L S^{2-})	ChV[d] (mg/L S^{2-})	IC25[e] (mg/L S^{2-})	NOEC (mg/L S^{2-})	LOEC (mg/L S^{2-})	ChV (mg/L S^{2-})	IC25 (mg/L S^{2-})
Sulfide + 0.8 mg Fe/L								
Activation	12.5	>12.5	>12.5	>12.5	12.5	>12.5	>12.5	>12.5
Emergence (%)[f]	3.1	7.8	4.9	3.5 (3.1–3.9)	1.6	3.1	2.2	3.9 (3.5–4.3)
Emergence (ET30)[f]	–	–	–	–	3.1	7.8	4.9	–
Survival	12.5	>12.5	>12.5	>7.8[g]	12.5	>12.5	>12.5	>7.8[g]
Shoot weight	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Shoot length	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Root weight	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Root length	–	–	–	–	7.8	12.5	9.8	7.6 (7.1–8.1)
Leaf number	12.5	>12.5	>12.5	>7.8[g]	7.8	12.5	9.8	>7.8[g]
Leaf biomass	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Phytotoxicity	12.5	>12.5	>12.5	>7.8[g]	12.5	>12.5	>12.5	>7.8[g]
Sulfide + 2.8 mg Fe/L								
Activation	12.5	>12.5	>12.5	>12.5	12.5	>12.5	>12.5	>12.5
Emergence (%)[f]	3.1	7.8	4.9	5.7 (5.3–6.1)	3.1	7.8	4.9	7.1 (6.5–7.7)
Emergence (ET30)[f]	–	–	–	–	3.1	7.8	4.9	–
Survival	12.5	>12.5	>12.5	>7.8[g]	12.5	>12.5	>12.5	>7.8[g]
Shoot weight	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Shoot length	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Root weight	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Root length	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Leaf number	12.5	>12.5	>12.5	>7.8[g]	7.8	12.5	9.8	>7.8[g]
Leaf biomass	–	–	–	–	7.8	12.5	9.8	>7.8[g]
Phytotoxicity	12.5	>12.5	>12.5	>7.8[g]	12.5	>12.5	>12.5	>7.8[g]
Sulfide + 10.8 mg Fe/L								
Activation	12.5	>12.5	>12.5	–	12.5	>12.5	>12.5	>12.5
Emergence (%)	3.1	7.8	4.9	8.5 (8.2–8.8)	3.1	7.8	4.9	9.3 (8.8–9.8)
Emergence (ET30)	–	–	–	–	3.1	7.8	4.9	–
Shoot weight	–	–	–	>12.5[g]	12.5	>12.5	>12.5	>12.5[g]
Shoot length	–	–	–	–	12.5	>12.5	>12.5	>12.5[g]
Root weight	–	–	–	–	12.5	>12.5	>12.5	>12.5[g]
Root length	–	–	–	–	12.5	>12.5	>12.5	>12.5[g]
Leaf number	12.5	>12.5	>12.5	>12.5[g]	12.5	>12.5	>12.5	>12.5[g]
Leaf biomass	–	–	–	–	12.5	>12.5	>12.5	>12.5[g]
Phytotoxicity	12.5	>12.5	>12.5	>12.5[g]	12.5	>12.5	>12.5	>12.5[g]

[a]Nominal concentrations.
[b]No-observed-effects concentration.
[c]Lowest-observed-effects concentration.
[d]Chronic value (geometric mean of NOEC and LOEC value). Represents the estimated threshold of toxicity.
[e]25% inhibitory concentration determined by linear interpolation with 95% confidence intervals in parentheses.
[f]No emergence recorded at 12.5 mg S^{2-}/L.
[g]Reported as greater than highest concentration in which mesocotyl emergence was observed. No emergence was noted in the 12.5 mg S^{2-}/L treatment with either 0.8 or 2.8 mg Fe/L.
NOEC = no-observed-effects concentration; LOEC = lowest-observed-effects concentration; ChV = chronic values; IC25 = 25% inhibitory concentration; ET30 = time to 30% emergence.

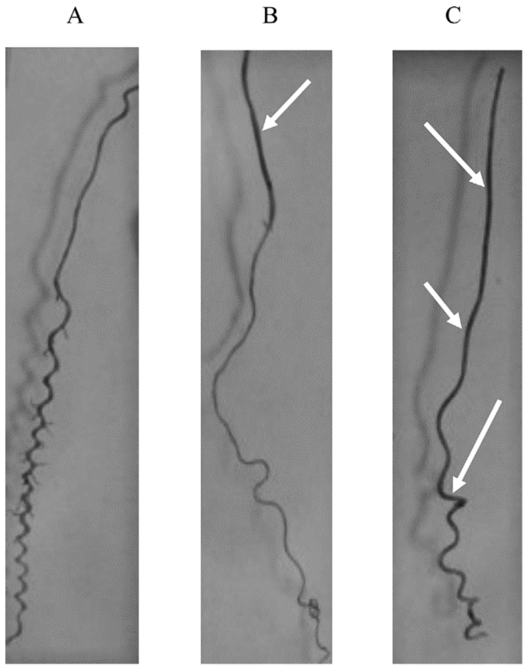

Figure 1. Representative seminal roots from (**A**) HS-1 control containing <0.01 mg/L sulfide and 0.8 mg/L Fe, (**B**) 7.8 mg/L sulfide with 2.8 mg/L Fe, and (**C**) 7.8 mg/L sulfide with 10.8 mg/L Fe. Note normal root fibers and absence of iron sulfide (FeS) plaque in seminal root from the control (**A**), increase in the formation of FeS plaque at the upper region (arrow) of the root in seminal root from the 7.8 mg/L sulfide with 2.8 mg/L Fe treatment (**B**), and more widespread FeS plaque (arrows) formed on the seminal root from the 7.8 mg/L sulfide with 10.8 mg/L Fe treatment (**C**).

However, the effects measured were on juvenile seedling growth and development using seedlings produced from seeds that were allowed to germinate and grow to 1 to 2 cm (over 5–7 d) in aerobic deionized water, whereas the present study initiated exposure in ungerminated seeds. Both studies utilized a modified Hoagland's solution [4,5], with the studies by Pastor et al. [23] containing one-fifth strength solution and 5 mM piperazine-N,N′-bis buffer and the present study using modified HS-1 solution [4] containing 25% ammonium (molar basis) in a mixture of ammonium and nitrate. The hydroponics design [24] used total hypoxia to maintain sulfide levels, but exposed the vegetative portion of the rice plants to levels of sulfide much greater than would be expected in nature. The design of the hydroponics system used in the present study allowed the seed, mesocotyl, and early primary leaf (shoot) to be exposed to the hypoxic media with sulfide, which was supported by peer review of studies supporting the re-evaluation of the State of Minnesota's surface water quality standard for sulfate [1,2]. More ecologically realistic test conditions were recommended by peer review [24], and thus the basis for the design was a scaled-down model of ponds in which wild rice grows naturally. The primary differences between the laboratory hydroponics study and rice growing naturally were the lack of sediment in the simplified, but highly controlled hydroponics and omission of the floating leaf phase. In the case of the hydroponics, allowing a floating leaf phase would have resulted in artificially greater exposure to sulfide because of the high levels of sulfide in the media, which are not generally present at the surface of pond water. Oxidation of free sulfide in the water column resulting from greater oxygen levels naturally reduces free sulfide levels exposed to the floating leaves of wild rice.

Based on measured sulfide concentrations, Fe substantially reduced free sulfide concentrations in the 10.8 mg Fe/L treatment relative to the 0.8 mg Fe/L treatment. The effect of 2.8 mg Fe/L on free sulfide concentrations fell between the 0.8 and 10.8 mg Fe/L treatments. These observations, combined with differences in wild rice responses to sulfide across different iron concentrations, demonstrate the ability of Fe to reduce sulfide toxicity to wild rice. Free sulfide loss between 24-h renewals ranged from 19.6 to 23.5% with 0.8 mg Fe/L, 32.4 to 55.6% with 2.8 mg Fe/L, and 87.6 to 95.4% with 10.8 mg Fe/L, based on time-weighted average measurements. The loss was presumably partly the result of degradation, but primarily complexation with iron. These results provide evidence that Fe reduces free sulfide concentrations, but not necessarily as a linear function of Fe concentration [25–27]. Sulfide levels in pond sediment are determined by sulfate levels, availability, temperature, oxidation-reduction potential, pH, total organic carbon, Fe^{2+} levels, and speciation [21,28]. In some cases, sediment Fe^{2+} concentration may be inadequate to detoxify the sulfide by deposition of iron sulfide (FeS), and only some sediment will exist as FeS, even with large amounts of Fe. Although less toxic than sulfide, FeS can adversely affect the root systems of aquatic plants. Sensitivity of grass species (including wild rice) to sulfide has been studied for many years. Since the late 1950s, sulfide phytotoxicity has been described historically by rotting roots, black (FeS plaque) root, leaf discoloration, and poor growth and yield [29–31] because of sulfide-induced nutritional deficiencies resulting from poor uptake and utilization of critical nutrients [20,22,29–33]. These deficiencies result in potential inhibition of various oxidases, compromising metabolic capacity, inducing oxidative stress, and reducing gas exchange [34–38] in the root systems. Detoxification of sulfide by rice requires radial oxygen loss from roots to the rhizosphere as described by Armstrong and Armstrong [29]. These investigators provided the first specific anatomical assessment of radial oxygen loss inhibition by sulfide, blockage of vascular systems, and inhibition of lateral root emergence in rice, which correspond to the toxicological impact on the rice plant. Armstrong and Armstrong [29] found that adventitious and fine lateral roots of rice exposed to sulfide had reduced radial oxygen loss to the rhizosphere atomically characterized as being thickened, resulting in inhibition of the apical cortical gas space system. More recent studies [39,40] have demonstrated mitochondria-based detoxification of sulfide primarily in the roots. Functional isoforms of O-acetylserine-(thiol)lyase C (OASTL), specifically OAS-C, detoxify sulfide primarily in the roots [41] by catalyzing the conversion of sulfide and O-acetylserine to cysteine.

In the present study, black plaque was found on the seminal roots exposed to >7.8 mg/L sulfide and 2.8 or 10.8 mg/L Fe. However, root blackening is often observed in plants growing in sulfide-laden sediment. In the present hydroponics study, limited root blackening was found, as expected, because sediment cofactors such as organic carbon and microbial flora are likely required to facilitate the process. Although it is plausible that OAS-C was responsible for detoxifying a portion of the sulfide to which the wild rice seedlings were exposed in the present study; based on the daily rate of sulfide decay (~30%), the seedlings were still exposed to a significantly high level of free sulfide during the study. Thus, enzymatic sulfide detoxification in the roots cannot explain the decreased toxicity of sulfide we observed even at the lower Fe concentration on a physiological level. Sulfide toxicity to wild rice is also tissue dependent, with the mesocotyl and roots being less susceptible to free sulfide toxicity and the photosynthetic portion being more susceptible to sulfide. On a larger scale, to properly evaluate sulfide toxicity to wild rice, both free sulfide and complexed sulfide need to be considered, based on the appearance of black plaque on the roots of wild rice seedlings from the higher sulfide and Fe treatments and the reduction in free sulfide toxicity by Fe found in the present study.

CONCLUSIONS

The results of the present study indicate that exposure of developing wild rice (mesocotyl emergence) to sulfide-induced toxicity $\geq$3.1 mg/L sulfide in the presence of 0.8 mg Fe/L, and $\geq$7.8 mg/L sulfide in the presence of 2.8 or 10.8 mg Fe/L at study day 21. Mesocotyl emergence was the most sensitive endpoint, and growth endpoints were less sensitive. Increasing Fe concentrations reduced the toxic effects of sulfide to wild rice. Ultimately, determination of site-specific sulfate criteria considering factors that alter toxicity, including sediment Fe and organic carbon, are necessary to adequately address the potential impact of sulfate in surface waters. Additional study of the larger significance of the hydroponics study is warranted, taking into account an aquatic life cycle evaluation of sediment sulfide toxicity to wild rice using a sediment microcosm.

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Data availability—Data, associated metadata, and calculation tools are available from the corresponding author (djfort@fortlabs.com)

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Analyses of the connection between water body chemistry and wild rice.

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Executive Summary

My comments relate to Chapter 1 , C, D, E and F of the *Final Technical Support Document Refinements to Minnesota's Sulfate Water Quality Standard to Protect Wild Rice*. The data set used in the study (the "Class B" data set) comprises 108 water bodies. Some analyses use a 96-body subset of the Class B data set – those water bodies with transparency greater than 30 cm, which is thought to make them more suitable for wild rice. Relevant variables include four analytes – porewater sulfide, porewater iron, porewater total organic carbon, and surface water sulfate – abbreviated in the discussion below to "sulfide, Fe, TOC and SO4." Also measured was the presence or absence of wild rice, and (where wild rice was present) its stem density. Analyses were carried out in R Version 3.3.0. Weisberg (2014) and Fox and Weisberg (2011) are general references to the statistical methodology and its execution in R.

The analyses led to the conclusions:

1. The waterbody-specific sulfate standard proposed by MPCA does not differentiate waterbodies hosting wild rice from water bodies that do not.
2. More generally I have been unable to find any function of SO4, TOC and Fe that can differentiate water bodies hosting wild rice from water bodies that do not.
3. Sulfide is a statistically significant but weak predictor of wild rice presence.
4. The MPCA assessment of the proposed sulfate rule's performance is questionable.
5. All four analytes vary substantially from time to time within the same water body.
6. SO4, TOC and Fe are statistically significant but imprecise predictors of sulfide.
7. The proposed sulfide cutoff of 120 μg/L is not well supported and would lead to many false alarms.
8. A different approach using sulfide in a linear discriminant analysis incorporates explicit recognition of the implications of false positive and false negatives, and further motivates higher sulfide cutoffs.

In summary, the data presented give little reason to believe that changes in the sulfate standard will have any effect on the occurrence or health of wild rice, or indeed that a sulfate standard itself is required. A standard focused directly on sulfide would incur substantial numbers of false positives (water bodies with high sulfide but abundant wild rice) and false negatives (water bodies with low sulfide but no wild rice). More detailed study of these water bodies would be required to diagnose their specific properties and actions needed to enhance wild rice.

Analyses

1. *The waterbody-specific sulfate standard proposed by MPCA does not differentiate waterbodies hosting wild rice from water bodies that do not. This refers to Chapter 1 E Development of an equation to calculate a numeric sulfate standard for each wild rice water*

The Class B data set discussed in the MPCA document and analyzed here comprises 108 wild rice water bodies. As there is reason to believe that opaque water is inhospitable to wild rice, some of MPCA's analyses are restricted to 96 water bodies whose transparency exceeds 30 cm. This thinning can be justified by the observation that 11 of the 12 water bodies excluded did not have wild rice and only one did.

Directly cross-tabulating all 108 water bodies by the presence or absence of wild rice, and whether their SO4 is above or below the MPCA's Chapter 1E water-body-specific sulfate limit gives the table:

MPCA limit all water bodies

	SO4 high	SO4 low	total
Rice absent	24	17	41
present	48	19	67
Total	72	36	108

A formal test of the association between SO4 and wild rice presence is given by Pearson's chi-squared test:

```
        Pearson's Chi-squared test with Yates' continuity correction
X-squared = 1.4203, df = 1, p-value = 0.2334
```

The P value of this test falls far short of statistical significance, confirming the visual impression that the proposed SO4 limit has no connection to the presence or absence of wild rice in the water body. Another indication of this is the total concordance – the proportion of water bodies correctly classified as wild-rice-hospitable or not by whether their SO4 is above or below the limit:

```
Concordance and CI    39.8%    31.1%    49.2%
```

In other words, 60% of the water bodies – a majority – would be misdiagnosed by the proposed standard.

Restricting the analysis to the 96 water bodies with suitable transparency gives the same conclusions:

MPCA limit 96 water bodies

	SO4 high	SO4 low	total
Rice absent	18	12	30
present	47	19	66
Total	65	31	96

```
        Pearson's Chi-squared test with Yates' continuity correction
X-squared = 0.7285, df = 1, p-value = 0.3934

Concordance and CI    38.5%    29.4%    48.5%
```

FINDING 1: In both the broader and the narrower data sets, there is no association between the presence or absence of wild rice and whether the SO4 is above or below the waterbody-specific sulfate limit.

The performance of the proposed sulfate standard for identifying wild rice sites is akin to throwing a die and declaring the water body good if the die shows a 1 or 2, and bad if the die shows a 3, 4, 5 or 6.

2. *More generally I have been unable to find any function of SO4, TOC and Fe that can differentiate water bodies hosting wild rice from water bodies that do not.*

Concentrating on the 96-water-body data set of sites where the water is transparent enough to be thought amenable to wild rice, presence or absence can be modeled directly from SO4, TOC and Fe with a logistic regression:

```
glm(formula = Presence ~ logSO4 + logTOC + logFe, family = binomial)

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)   4.3819     2.4913   1.759   0.0786 .
logSO4       -0.5050     0.3309  -1.526   0.1269
logTOC       -0.2771     0.4968  -0.558   0.5770
logFe        -0.7979     0.6716  -1.188   0.2348

    Null deviance: 119.25  on 95  degrees of freedom
Residual deviance: 115.34  on 92  degrees of freedom
Explained            3.91  on  3  degrees of freedom
```

The overall model has an explained deviance of 3.91 with 3 degrees of freedom for a P value of 0.2713.

Thus neither the overall model, nor any of the terms in it, is statistically significant.

The same conclusion comes from a logistic regression using all 108 water bodies – neither the overall logistic regression, nor any of its terms, is statistically significant.

Another view of the data set is given by Hoteling's multivariate T squared test, which tests whether there is any difference in the triad log(SO4, TOC, Fe) between the water bodies that do and that do not harbor wild rice. In the 96-water-body set, this test gives:

```
F-statistic: 1.283 on 3 and 92 DF,  p-value: 0.285
```

confirming the lack of significant difference in these three concentrations between the water bodies that do and do not host wild rice.

The conclusion then is that these three predictors are not informative about the presence or absence of wild rice. Any model using them to predict presence or absence of wild rice can be no better than random guessing.

It is however conceivable that, even though these predictors cannot predict presence or absence of wild rice, they might nevertheless be able to differentiate water bodies with healthier wild rice. To explore this possibility, a linear regression of the stem density was fitted with the following results

```
Call:
lm(formula = Stems ~ logSO4 + logFe + logTOC, data = DDt)

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
```

```
(Intercept)   33.675     47.627   0.707    0.481
logSO4        -7.481      6.400  -1.169    0.245
logFe          3.840     13.143   0.292    0.771
logTOC        -8.925      9.395  -0.950    0.345

Residual standard error: 42.82 on 92 degrees of freedom
Multiple R-squared:  0.01834,   Adjusted R-squared:  -0.01367
F-statistic: 0.573 on 3 and 92 DF,  p-value: 0.6342
```

Neither the overall regression nor any of the terms in it is statistically significant, showing that SO4, Fe and TOC are not relevant in this context either.

FINDING 2: Whether for wild rice presence, or for the abundance of the wild rice, SO4, TOC and Fe do not show any predictive information in the field data.

3. *Sulfide is a statistically significant but weak predictor of wild rice presence. This refers to Chapter 1C. Identification of 120 μg/L as the protective sulfide concentration.*

External evidence cited in the document shows the potential for harm to wild rice from sufficiently high concentrations of sulfide, and sulfide is described in the MPCA document as a primary determinant of the presence of wild rice. The predictive power for sulfide can be quantified by a logistic regression of wild rice presence or absence on log sulfide within the full data set. This gives

```
glm(formula = Presence ~ log10(Sulfide), family = "binomial")
Coefficients:
               Estimate Std. Error z value Pr(>|z|)
(Intercept)     -0.7089     0.4567  -1.552  0.12059
log10(Sulfide)  -1.3373     0.4522  -2.957  0.00311 **

Null deviance: 143.40  on 107  degrees of freedom
Residual deviance: 132.87  on 106  degrees of freedom
```

On the one hand, logsulfide is indeed a highly statistically significant predictor (P=0.00311).

On the other hand, however, sulfide explains only 10.53, or 7%, of the total deviance in wild rice presence, leaving the remaining 132.87, or 93% unexplained.

Performing the same calculation on the 96 water body data set gives the same substantive conclusions. The P value for sulfide in the regression is a 0.0114, still significant though not quite as strong as the full data set. However in this data set, sulfide explains an even-smaller 6% of the total deviances, leaving 94% unexplained.

This means that while porewater sulfide is a statistically significant part of the picture of wild rice presence or absence, it is only a modest part of it. Its contribution pales next to that of other characteristics and variables.

Exploring this further, receiver operating characteristic (ROC) curves are a standard methodology for exploring the ability of a predictor *X* to classify cases into a "good" and a "bad" class. The sensitivity associated with any cutoff *C* is the proportion of bad cases whose predictor *X* exceeds *C* and which are therefore correctly classified at the cutoff *C*. The false positivity FP associated with *C* is the proportion of good cases whose *X* exceeds *C* and so are wrongly classified*.* The specificity is 1 – FP: the proportion of good cases whose *X* does not exceed *C* and which are therefore correctly classified at the cutpoint *C.* Sensitivity, specificity and FP are often expressed as percentages.

The ROC is a plot of sensitivity versus FP, generated by varying *C* across the whole range of the data. A widely-used guidance (CLSI EP24 A2) discusses the use of ROC curves.

The ROC curve of a good classifier rises steeply from the origin before turning over and going to the point (1,1). The ROC of a worthless predictor would be a straight line from the origin to the point (1,1).

The area under the ROC curve, the AUC, is a summary measure of the ability of *X* to distinguish good from bad cases. The AUC is 1 for a classifier that separates good cases from bad perfectly, and is 0.5 for a worthless classifier. The AUC has a direct interpretation. In our context, if you take one random water body with wild rice and one without, the AUC is the probability that the one without wild rice has higher sulfide than the one with wild rice.

There is a formal statistical significance test, the Wilcoxon test, for whether the AUC is significantly better than 0.5, that is, whether *X* does better than blind guessing.

The ROC curve for sulfide and wild rice presence in the full data set is shown as Figure 1. Its AUC is 0.653. The Wilcoxon test gives P = 0.0069 showing that using the sulfide level perform significantly better than blind guessing. But the actual AUC of 0.653, though statistically significant, is much closer to the 0.5 you get by flipping a coin than it is to 1. While, at 65.3%, a water body without wild rice has a better than 50% chance of a higher sulfide levels than a water body with wild rice, its odds are not much better.

Like the proportion of deviance explained, the AUC paints a picture of sulfide as one fairly small part of the picture: statistically significant but far short of determinative.

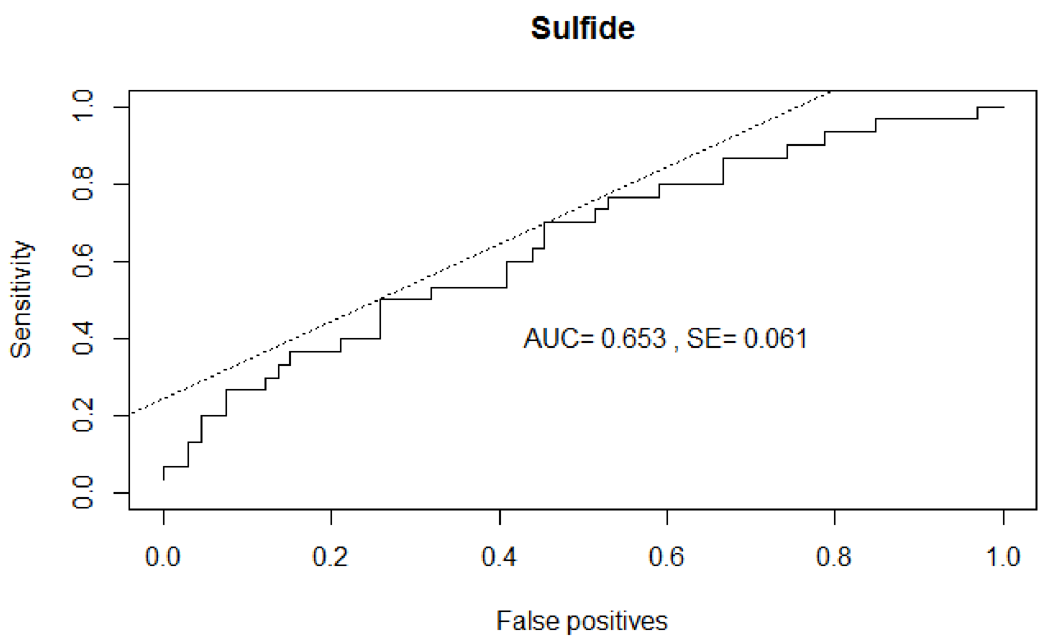

Figure 1. ROC curve for Class B waterbodies.

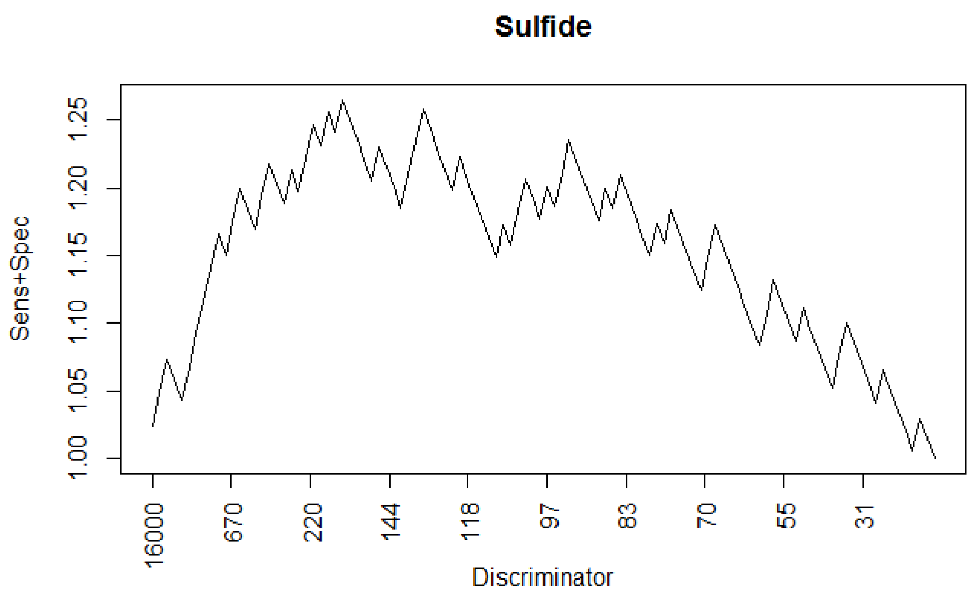

Figure 2. Youden index for different cutpoints.

The ROC curve also provides an objective way to determine a cutpoint. In an ideal situation, the ROC rises steeply to an "elbow" high up on the left of the graph, before leveling off and completing its path to the point (1,1). Such an elbow, when one exists, represents a natural cutpoint. The Youden index, defined as "sensitivity + specificity", is an overall measure of the desirability of the associated cutpoint. A conventional way of selecting a cutpoint is to pick the value maximizing the Youden index, this being, arguably, the point "highest on the left." Figure 2 is an aid to this; it shows the Youden index as a function of the sulfide cutpoint.

The maximum Youden index is 1.265, given by a sulfide cutpoint of ***181 μg/L***

But figure 2 also shows that the Youden index exceeds 1.2 for most cutoff values between 118 and 305, indicating that within this range, sensitivity and specificity are essentially trading off on a one for one basis and implying that a case could be made for any value within this range.

Repeating the ROC analysis on the subset of 96 water bodies with transparent water gave a slightly smaller AUC of 0.653 with less significance, P=0.0172, and leading to a Youden index of 1.245 at the cutpoint 0.093, somewhat below the values indicated for the full data set.

Another perspective on possible cutpoints comes from a changepoint analysis. The methodology of Hawkins (2001) was applied to the 96-body data set to find the cutpoint that optimally distinguishes the water bodies with wild rice from those without on the basis of their porewater sulfide. In this analysis, the optimal cutpoint was ***274 μg/L.***

FINDING 3.1: Sulfide has a statistically significant separation between water bodies with and without wild rice, but is not particularly effective in differentiating between the two.

FINDING 3.2: The ROC curve does not identify a clear choice for a cutpoint on sulfide.

4. *The MPCA assessment of performance is questionable. This refers to Chapter 1 F Comparison of an equation-based standard to fixed standards: Error rates and concerns.*

Contrary to my conclusion that SO4 has no perceptible connection to wild rice, the MPCA document reports quite favorable performance for the proposed water-body-specific sulfate standard. However this performance is against a surrogate endpoint – sulfide being below 120 μg/L – and not the actual endpoint of interest – the presence or absence of wild rice.

Surrogate endpoints are acceptable in some circumstances, notably

- when the surrogate is more easily available, or available sooner, than the primary endpoint; and
- the surrogate endpoint is closely related to the primary endpoint.

Neither of these circumstances motivating surrogate endpoints appears relevant in this problem. It is implausible that measuring the chemistry of a water body is faster, cheaper or more convenient than a visual assessment of its vegetation. On the second requirement, sulfide is a quite imperfect predictor of wild rice presence and health, a deficiency that the MPCA report itself notes.

FINDING 4: Thus the use of this surrogate endpoint seems questionable, as do the resulting conclusions.

5. *All four analytes vary substantially from time to time within the same water body. This relates to Chapter 1D Assumption that SO4, TOC, iron and sulfide are in a steady state at field sites.*

Some water bodies were sampled more than once, but where a body had more than one measurement, MPCA's primary analyses used only one. Their analysis invoked the "steady state" concept that the water body chemistry does not change much over time, and it is appropriate to check on this.

The data set "MPCA_Field_Survey_Data_with_calculated_protective_sulfate_concentration" contained 267 records covering 165 waterbodies. Of these, 53 bodies provided more than one record of some or all of the key variables sulfide, SO4, Fe and TOC. The repeat measurements at the same water bodies were taken at different dates. The standard deviation of the sampling date within a waterbody was 210 days, or some 7 months.

The multiple readings of these measures within the same water body were analyzed by a random effects analysis of variance to separate out the variability within and between water bodies. Calculations used the "lmer" command from the R package "lme4". To correct for any major seasonal effects, the model included sine and cosine terms with period one year and six months.

All four of the concentrations were transformed to common logs.

This results of this analysis follow.

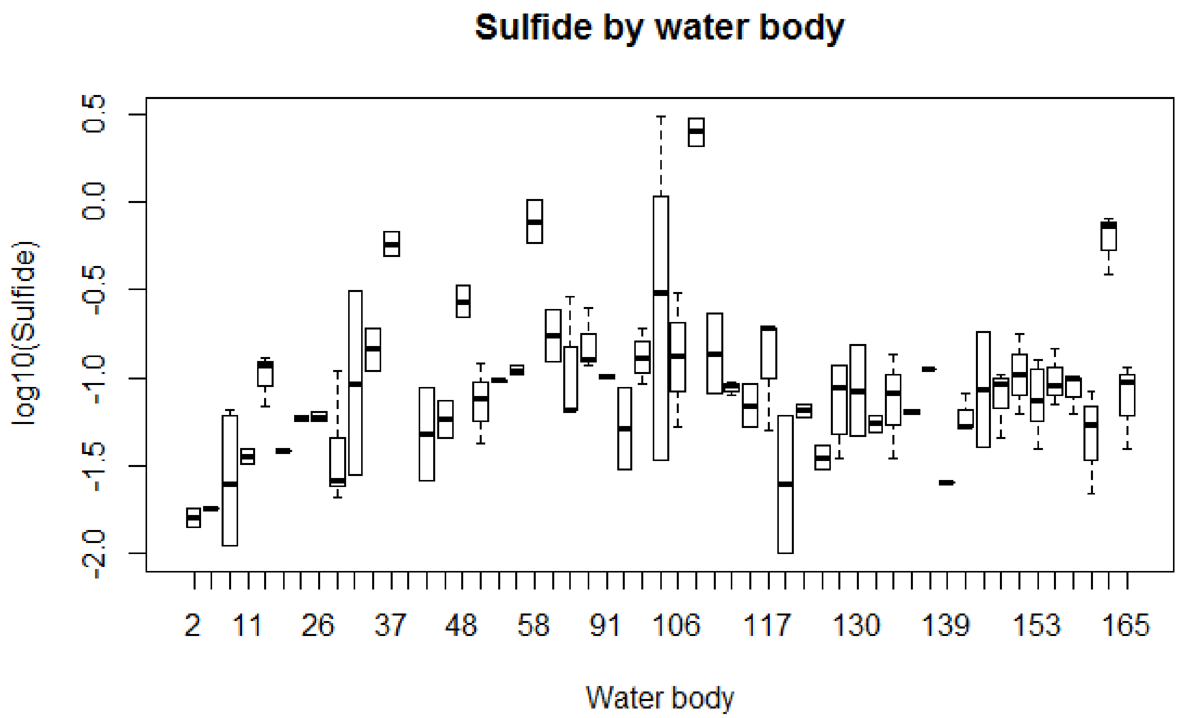

Figure 3. Sulfide repeat sampling

Figure 3 is a comparative box and whisker plot of the log-transformed sulfide values measured at different times broken down by waterbody. Visually, the plot shows variability within a water body comparable in scale to that between water bodies. This visual impression is quantified by the analysis of variance. In this, the term "keeplake" corresponds to variation from one water body to another; "Residual" refers to variation over time within a water body.

```
REML criterion at convergence: 129.3
 Random effects:
  Groups   Name        Variance Std.Dev.
  keeplake (Intercept) 0.10763  0.3281
  Residual             0.08246  0.2872
```

The log-transformed sulfide level varies from one water body to another with a standard deviation of 0.33. However within the same water body, it varies from one time to another with a similar standard deviation of 0.29. A standard deviation of 0.29 on the log10 scale corresponds to a coefficient of variation of about 70% on the original scale. At this level, two sulfide readings on the same water body have a 1 in 3 chance of differing by more than 100%, a proportion supported by the actual successive sulfide readings.

In other words, the sulfide level of a water body is an elusive, moving target.

Fe

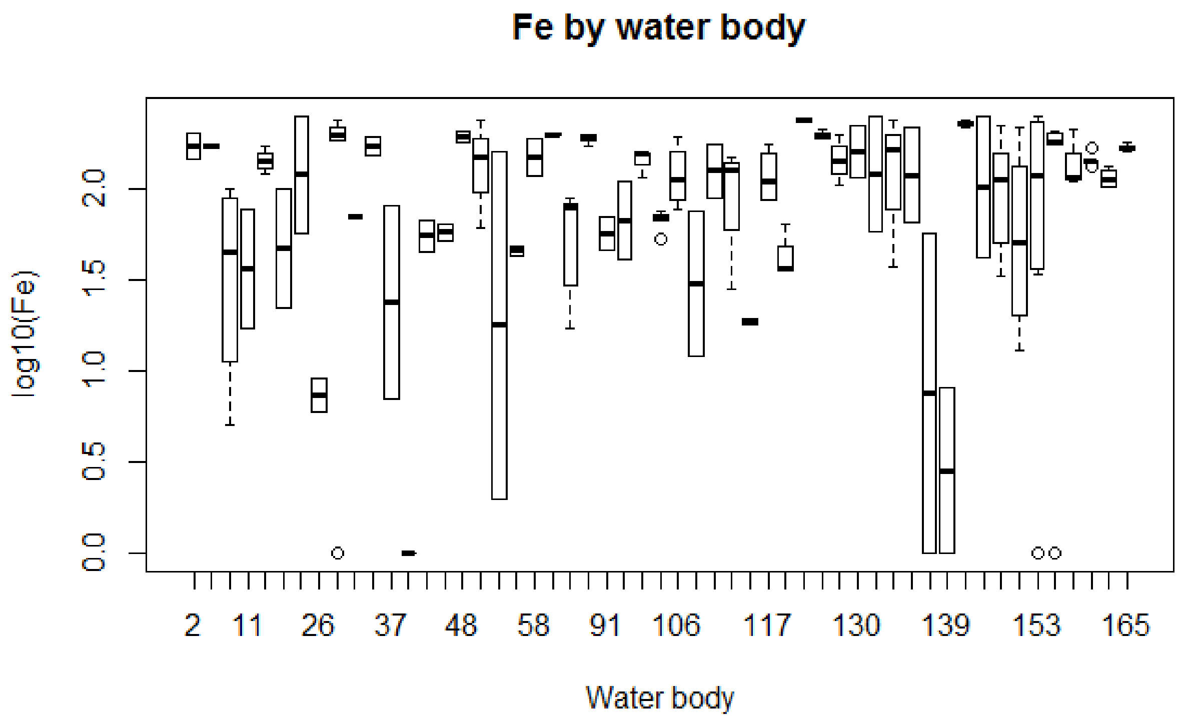

Figure 4. Fe repeat sampling

Figure 4 shows the same picture of the log-transformed iron level. This too is visually highly variable within a water body. The analysis of variance gives

```
REML criterion at convergence: 257.8558
Random effects:
 Groups   Name        Std.Dev.
 keeplake (Intercept) 0.3376
 Residual             0.4776
```

The standard deviation within a water body is considerably higher than that between water bodies.

As the four concentrations have been log transformed, they are dimensionless, and it is legitimate to compare the standard deviations of the different analytes. Thus one can note that the variability in Fe from one water body to another is comparable to that of sulfide, but within a water body, Fe is considerably more variable than sulfide.

TOC

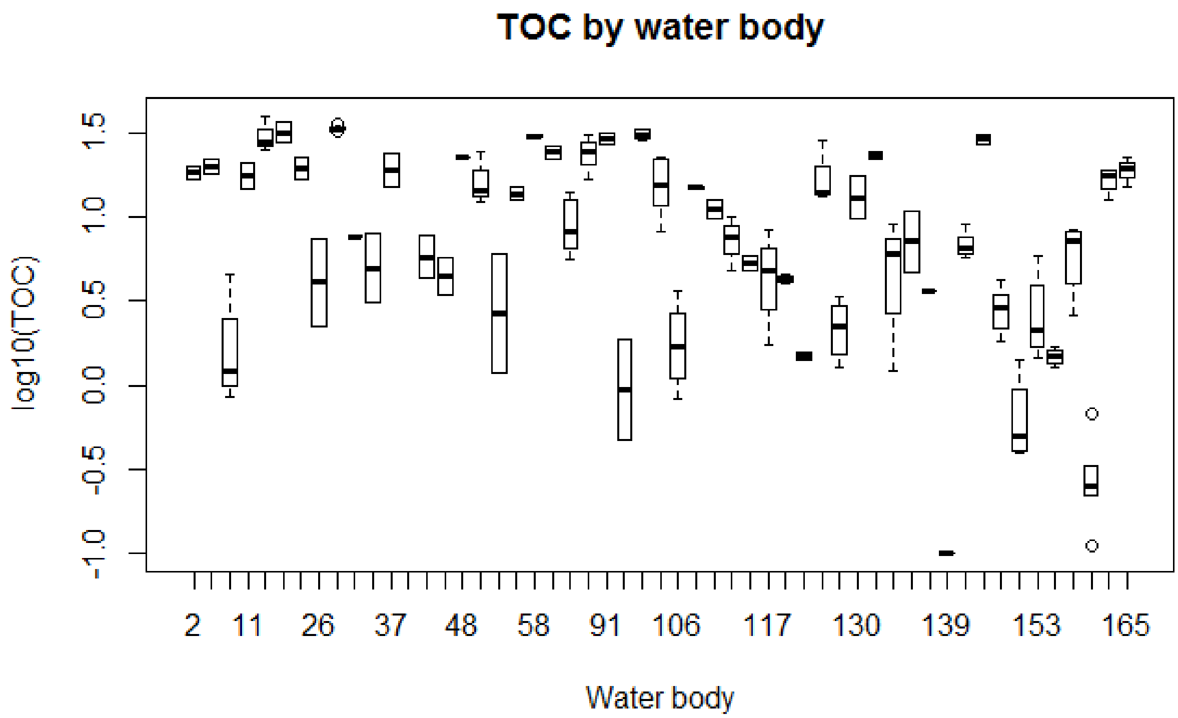

Figure 5. TOC repeat sampling

Figure 5 gives the box and whisker plot for log-transformed total organic carbon. The analysis of variance gives

```
REML criterion at convergence: 107.494
Random effects:
 Groups   Name        Std.Dev.
 keeplake (Intercept) 0.5401
 Residual             0.2013
```

TOC within a water body is much more stable that Fe or sulfide, but it varies more from one water body to another.

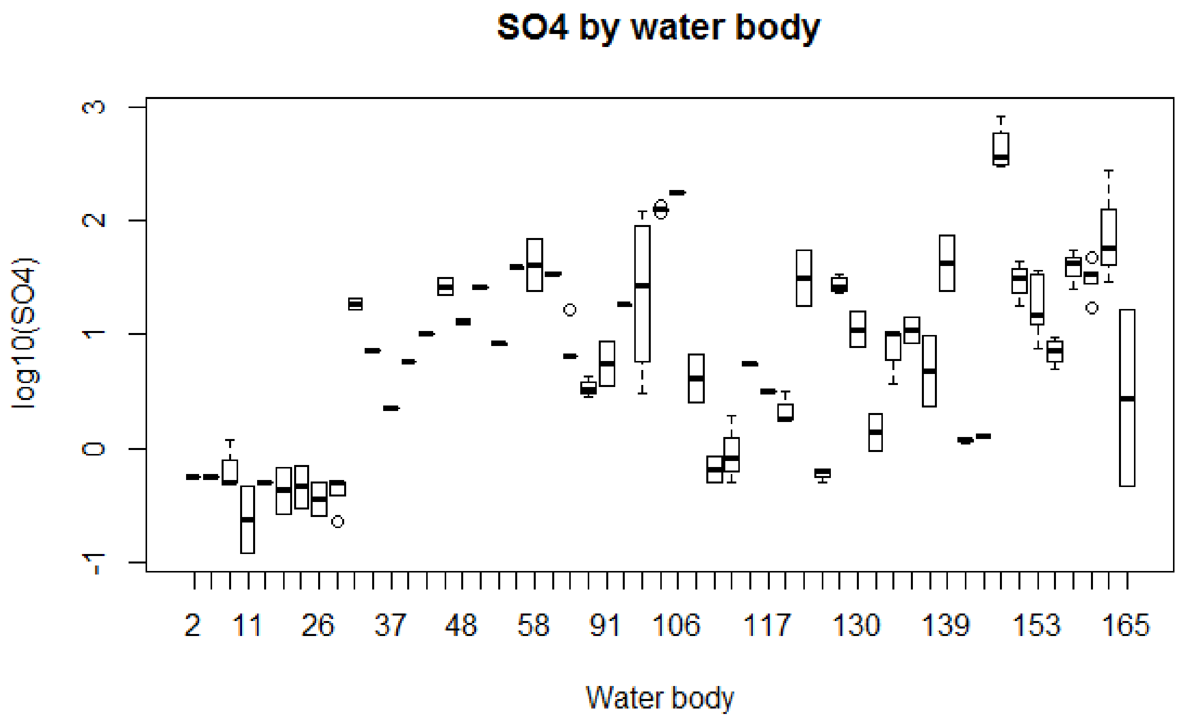

Figure 6. SO4 repeat sampling

Finally, Figure 6 shows log-transformed SO4. The analysis of variance gives

```
REML criterion at convergence: 185.077
Random effects:
 Groups   Name        Std.Dev.
 keeplake (Intercept) 0.7556
 Residual             0.2517
```

SO4 varies much more between waterbodies than do sulfide, Fe and TOC, and its variability within a water body is comparable with that of sulfide and TOC.

FINDING 5: In summary, all four analytes show substantial variability over time within the same water body. A snapshot of the chemistry at a given time may produce substantially different values than one made at another time. The steady state assumption is therefore not validated particularly well.

6. *SO4, TOC and Fe are statistically significant but imprecise predictors of sulfide. This refers to Chapter 1 C. Relationship between surface water sulfate and porewater sulfide.*

The regression model connecting sulfide to SO4, TOC and Fe in the full data set is:

```
lm(formula = logsulfide ~ logSO4 + logTOC + logFe

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  0.97145    0.38938   2.495   0.0142 *
logSO4       0.40241    0.05368   7.497 2.27e-11 ***
logTOC       0.45564    0.07832   5.818 6.65e-08 ***
logFe       -0.69130    0.10748  -6.432 3.91e-09 ***

Residual standard error: 0.3751 on 104 degrees of freedom
Multiple R-squared:  0.491,     Adjusted R-squared:  0.4763
F-statistic: 33.44 on 3 and 104 DF,  p-value: 3.253e-15
```

As expected, all three terms in the model are highly statistically significant, as is the overall regression. However, while significant, the regression explains less than half the variability ($R^2 = 0.491$), implying that other factors and random variability are responsible for most of the sulfide variability.

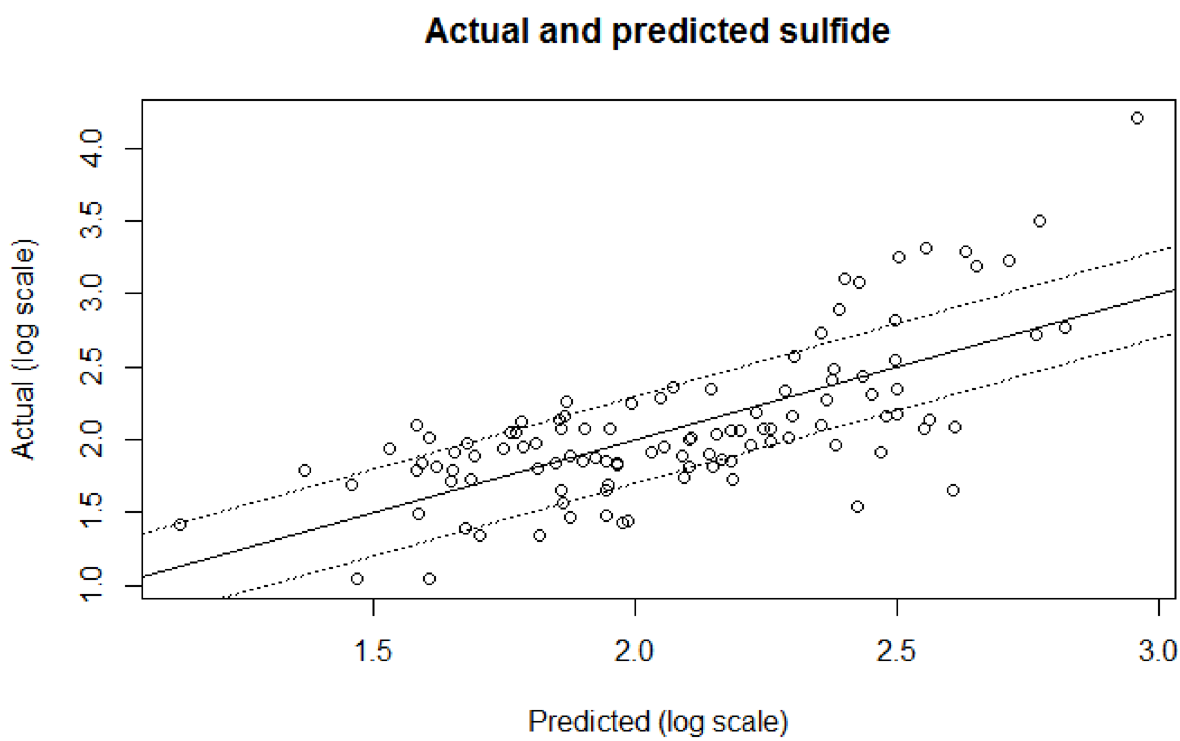

Figure 7. Predicting sulfide from SO4, FE and TOC

Figure 7 shows this graphically. It is a plot of the actual sulfide values against the value predicted by the regression on SO4, Fe and TOC. The plot is on a double log scale. The solid line is the line of identity.

The two dotted lines mark where the actual sulfide differs from the model prediction by a factor of 2. As the graph makes clear, the actual sulfide level quite commonly differs from its prediction by this factor of 2 or more. This is shown by the points lying outside the dotted lines.

FINDING 6.1 In other words, the highly significant regression nevertheless makes sulfide predictions that are commonly wide of the mark.

FINDING 6.2: Putting various pieces of the puzzle together,

- ***There is a statistically significant but imprecise relationship of SO4, Fe and TOC to sulfide, and***
- ***There is a statistically significant but modest relationship of sulfide to wild rice.***
- ***This chain of relationships falls apart when the intermediate of sulfide is removed and one attempts to predict wild rice directly from SO4, Fe and TOC. Then the unexplained variability in the two relationships overwhelms the modest associations, leading to the lack of significant association between SO4, Fe and TOC and the presence or absence of wild rice.***

7. *The proposed sulfide cutoff of 120 μg/L is not well supported and would lead to many false alarms.*

Continuing with the possibility of using the sulfide level as a classifier and taking a closer look at some proposed cutoffs, the usual measures of performance at the MPCA's 120 μg/L applied to the 96 water bodies with acceptable transparency are

```
          Cutoff 120
            Sulfide high Sulfide low total
Rice absent          15          15    30
present              18          48    66
Total                33          63    96
Sensitivity and CI    50.0%    33.2%    66.8%
Specificity and CI    72.7%    61.0%    82.0%
Sens + Spec and CI   122.7%   101.9%   143.6%
Concordance and CI    65.6%    55.7%    74.4%
PPV and CI            45.5%    29.8%    62.0%
NPV and CI            76.2%    64.4%    85.0%
```

The sensitivity, specificity and Youden index (sensitivity + specificity) have been mentioned. Looking beyond them to the outcomes of testing, the positive predictive value, PPV, is the probability that a high sulfide truly corresponds to lack of wild rice. This highly relevant as it tells you what fraction of followup after a signal of high sulfide will be productive in identifying genuine problems.

At the 120 μg/L cutoff, the PPV is less than 50%. The majority of high sulfides will therefore be false alarms and so most of the effort involved in following up high sulfide values will be wasted.

The negative predictive value, NPV, is the mirror image of this – the probability that a water body with sulfide below the cutoff does indeed host wild rice. A high NPV would imply that the water bodies that are categorized as good on the basis of low sulfide most likely are good and do not need much attention.

The NPV of 76.2% is fair to good. It does however mean that a quarter of the water bodies with this low sulfide level nevertheless do not have wild rice, leading one to wonder whether some simple intervention might bring wild rice to these water bodies,

The concordance, 65/96 = 66%, is the proportion of water bodies identified correctly.

The corresponding figures for the 181 μg/L that optimizes the Youden index, and the 274 μg/L that optimizes the changepoint test are:

Cutoff 181

	Sulfide high	Sulfide low	total
Rice absent	11	19	30
present	10	56	66
Total	21	75	96
Sensitivity and CI	36.7%	21.9%	54.5%
Specificity and CI	84.8%	74.3%	91.6%
Sens + Spec and CI	121.5%	102.2%	140.8%
Concordance and CI	69.8%	60.0%	78.1%
PPV and CI	52.4%	32.4%	71.7%
NPV and CI	74.7%	63.8%	83.1%

Cutoff 274

	Sulfide high	Sulfide low	total
Rice absent	8	22	30
present	6	60	66
Total	14	82	96
Sensitivity and CI	26.7%	14.2%	44.4%
Specificity and CI	90.9%	81.6%	95.8%
Sens + Spec and CI	117.6%	100.3%	134.9%
Concordance and CI	70.8%	61.1%	79.0%
PPV and CI	57.1%	32.6%	78.6%
NPV and CI	73.2%	62.7%	81.6%

The higher cutoffs give progressively better concordance, going from 66% to 71% as the cutoff goes from the MPCA's suggested 120 μg/L to the Youden optimum of 181 μg/L and the changepoint optimum of 274 μg/L. The PPV increases substantially, going from 45.5% to 57.1% indicating that effort spent in diagnosing high sulfide values is spent more productively.

The NPV decreases slightly, from 76% to 73%. This means that the clean bill of health coming from a sulfide below the cutoff becomes less clean as the cutoff increases. However the small change – from 76% to 73% -- shows that the reduction is not substantial.

FINDING 7: In summary, going from a sulfide cutpoint of 120 to 274 μg/L produces many fewer alarms, and those alarms that are produced are much more likely to indicate real problems with the wild rice.

8. Discriminant Analysis Approach using Sulfide

The problem faced in monitoring water body chemistry is a decision – on the basis of the current chemistry, deciding whether or not to flag the water body as suspicious of being inhospitable to wild rice and requiring closer investigation. The conventional statistical model for this problem is a linear discriminant analysis (LDA, Anderson 2003, Chapter 6). Unlike the other calculations made so far, LDA pays explicit attention to the tradeoff between the consequences of dealing with false positives and with false negatives.

It was applied to the 96 water bodies transparent enough to be thought hospitable for wild rice.

Using *X*, the common log of the sulfide as the discriminator, these water bodies fall in two populations:

1. Those in which wild rice is absent, of which there are 30,
2. Those in which wild rice is present, of which there are 66.

The sulfide data from the 96 water bodies of interest give summary statistics

Mean of *X* in population 1 = 2.26
Mean of *X* in population 2 = 1.96
Pooled variance = 0.22

Following Anderson section 6.5.1, the optimal classification rule is to classify a water body as suspect if its sulfide value satisfies

$$\frac{X - 0.5(2.26 + 1.96)}{0.22}(2.26 - 1.96) > \log_e k$$

The constant *k* is defined as

$$k = \frac{q_2}{q_1} R, \quad \text{where } R = \frac{L(1|2)}{L(2|1)}$$

The constants q_1 and q are the proportions of water bodies that do not, and do harbor wild rice. In the 96-body data set, it is reasonable to estimate the ratio q_2/q_1 by 66/30, the proportions in the data set.

The constants *L* reflect the "loss" incurred by the two types of potential misclassification. $L(1|2)$ is the loss when you declare a water body suspect when in fact it can harbor wild rice, and $L(2|1)$ is the loss when you declare a water body acceptable when in fact it can not harbor wild rice. Note that only the ratio of these numbers, and not their actual values, is relevant.

Solving the optimal classifying equation for *X* using these values for q_1 and q_2 classifies the water as suspect if

$$X > 2.11 + \frac{0.22}{0.30}\left(0.79 + \log_e R\right) = 2.69 + 0.73 \log_e R$$

Values for the ratio *R* could be found by considering the follow-up steps needed to determine that the classification was wrong and evaluating how onerous they are, but a sensitivity calculation is illustrative.

Consider the values *R* = 0.5, 1 and 2, ranging from the two types of error being equally severe to one being twice as bad as the other. These values of *R* lead to the sulfide cutoffs

R	Cutoff (µg/L)
0.5	153
1	490
2	1570

FINDING 8. Even the lowest of these numbers is above the 120 μg/L proposed in the MPCA document. These numbers provide further evidence that, if sulfide is used as an indicator of suitability for wild rice, a higher sulfide cutoff should provide a better use of resources for followup.

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SUMMARY

COMMENTS ON MINNESOTA POLLUTION CONTROL AGENCY

WILD RICE SULFATE / SULFIDE RULE MAKING SUGGESTIONS

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Summary

Increased focus on specific chemical characteristics of surface waters and associated sediment porewaters of wild rice (WR) areas may currently be non-warranted. Initially, system-wide biological and physical characteristics – specifically, competing vegetation and water depth – of waters containing WR should be the focus, if promoting WR abundance and production in that resource is the overall objective. Multiple examples of each of these influences can be observed occurring independently or, as is sometimes the case, concurrently. Based on historical, and current data and observations during laboratory and field experiments, as well as direct field-scale application via WR restoration activities, controlling competing vegetation and maintaining an appropriate water depth for WR should be the first two objectives for maintaining waters for increased WR growth, health, and abundance.

Comments and examples contained in this document will focus specifically on the following:

- Controlling competing vegetation in waters intended for WR production is critical for maintenance of desired WR growth, distribution, abundance, and productivity. Competitive exclusion and potential allelopathic influences from competing vegetation can substantially limit WR health and productivity, with the potential for elimination from the area or water resource.
- Achieving and maintaining an appropriate water depth in WR areas is the more important variables to control for WR plant growth, development, reproduction, and abundance. In the absence of appropriate water depth control, WR plants will be under excessive stress, which may result in decreased health and abundance with subsequent elimination from an area or water resource.
- In general, for prairie potholes, in the absence of water depth control and maintenance of a preferable WR water depth, and the almost ephemeral nature of prairie potholes re: presence / absence of standing water, prairie potholes are unlikely to be acceptable habitat for WR production, regardless of chemical characteristics of overlying water and sediment pore water.
    - Prairie potholes are not generally controlled, or controllable, for WR production. Reference of prairie potholes as poor WR habitat specifically due to chemical characteristics that may be detrimental to (WR) growth is incomplete, and not necessarily defensible if not considering the variable hydrologic cycle(s) of any specific pothole.
- Suggesting that water lilies are indicative of acceptable WR habitat is an incomplete statement. In the system detailed here (Lake Monongalia, Kandiyohi County, New London, MN), WR and water lilies do occur in the same general area; however, a distinction between higher density populations of each plant appears evident. Therefore, simply stating that the presence of water lilies is an indicator of acceptable WR habitat is overgeneralized.

    - Multiple researchers (Elakovich and Wooten, 1989; Quayyum et al., 1999) have observed inhibitory allelopathic influences on WR health from extracts of water lily leaves and rhizomes. The possibility also exists for legacy inhibitory influences from water lilies towards WR during decomposition in aquatic sediments.
    - Additionally, water lilies have been observed to grow in areas of this system with water depths exceeding three feet – a depth not conducive to WR plant growth. In a system with non-controlled water depth, water lilies may be a high proportion of the aquatic plant assemblage in the absence of WR. This could also be due to a lack of viable WR seed in the sediment; a potential result of WR germination in excessive water depths without subsequent reproductive success.
- Based on available data, and consideration of biological, physical, and other environmental influences beyond control specific to microbial H2S synthesis, application and enforcement of a sediment porewater sulfide WR protective level is unlikely to be beneficial to WR distribution in MN. Furthermore, persistence of any measured concentration of H2S is not certain over multiple growing seasons.

1.0 INFLUENCES ON WILD RICE GROWTH, HEALTH, AND ABUNDANCE

As suggested at the public meeting in Virginia, MN, on October 24, 2017, increased focus on specific chemical characteristics of surface waters and associated sediment porewaters of wild rice (WR) areas may currently be non-warranted. Initially, system-wide physical and biological characteristics of waters containing WR should be the focus, if maintenance or management of that resource for WR production is the overall objective. Specifically, water depth and competing vegetation. Multiple examples of each of these influences can be observed occurring independently or, as often is the case, concurrently. One example which is highlighted in following sections is the increasing area of cattail dominance in areas once dominated by WR. Based on historical, and current data and observations during laboratory and field experiments, as well as direct field-scale application via WR restoration activities, maintaining an appropriate water depth for WR and managing competing vegetation should be the first two objectives for maintaining waters for increased WR growth, health, and abundance.

1.1 PHYSICAL INFLUENCES – WATER DEPTH

According to published literature sources water depths of 0.5 – 3.0 feet are more conducive to WR growth and propagation (MN DNR 2008; Vogt 2012), and that water depth is the major factor controlling WR abundance and production (Aiken 1989, Oelke et al. 1997, MN DNR 2008; Vogt 2012). Water depth directly influences WR phenological development and its ability to compete against other aquatic vegetation better able to cope with increased or increasing water depth (**Figures 1-3**). Current, on-going studies indicate that, under these experimental conditions, WR seeds germinated and grew at a depth from surface of 110 cm (~ 3.6 ft.). However, WR plants were not able to achieve aerial, or the later phenological reproductively mature (viable seed-bearing) stages within the growing season (**Figures 4-6**). Since WR is an annual (described below), if this scenario continues to occur under field-scale conditions, the viable seed source in the sediment will more likely be depleted, resulting in elimination of WR from that area or water resource.

Phenological development refers to the life stages of higher plants (angiosperms) from germination of the seed until death / senescence of the plant either after a single season (annuals; such as WR), two seasons (biennials), or multiple growing seasons (perennials). Unlike terrestrial grains, the shoot in WR emerges from the seed before the root (Aiken et al. 1989). WR uses this germination strategy because light and carbon dioxide availability limit early development of the seedling, as opposed to water availability in terrestrial plants. Seedlings rely on limited food reserves in the seed as they grow toward the surface of the water where light will not be limiting. Photosynthesis will only be optimized when light availability is not limited by overlying water, and when carbon dioxide levels increase by ~ 40x as the plant emerges into the atmosphere.

Weir and Dale (1960) give a good account of the development of the plant. Three forms of leaves develop – submerged, floating, and aerial – which differ in anatomical characteristics likely related to their physiological environment. The submerged leaves are thin and lack a cuticle, the outer waxy covering present on leaves of terrestrial plants. No stomata (tiny openings on the cuticle for gas exchange) are present. These leaves also have abundant air passages at this time which are known as lacunae, and greatly reduced conducting tissue (the vascular bundles or veins) which transport both water and sugars. The lacunae presumably help oxygenate the interior of the leaf and prevent the build-up of potentially problematic products common under anoxic conditions; while the veins are not as critical since water is not limiting and photosynthesis is not yet optimal. Two to three submerged leaves are normally formed while the plant grows to the surface. In late May to early June, the floating leaves appear. These differ from the submerged leaves by having a cuticle with stomata on the upper surface of the leaf (Hawthorn and Stewart 1970) and a well-developed mid vein on the lower surface which does not have a cuticle. Gaseous exchange is now possible with the atmosphere and the cuticle essentially makes the leaf 'waterproof' enabling the leaf to tolerate wetting from wave action. Two to three floating leaves are produced before the first emergent leaf emerges. These leaves have a well-developed vascular system with associated lacunae having compartments separated by diaphragms. Gaseous exchange is no longer an issue and now the plant concentrates on obtaining needed nutrients from the sediment while aerating the underwater organs via the lacunae and thus enhancing energy production via aerobic respiration. Most biomass production occurs in the aerial stage of development. The ratio of root:biomass also increases (Thomas and Stewart 1969) at this stage of development as the plant becomes better anchored. Another occurrence at this stage is that the shoot apex (vertical growing tip) changes from vegetative to reproductive growth (Weir and Dale 1960), triggering the rice plant to begin grain formation. The timing for this event in Northwestern Ontario varies depending on the environmental characteristics (depth, nutrients) of the individual sites and the depth tolerance of the seed source involved (Counts and Lee 1988), but would likely occur in most sites, including northeast Minnesota, towards the end of June with flower formation evident in early July. Timing of this developmental change may be delayed depending on how early in the growing season the plant was able to begin floating leaf and aerial stage growth. Water depth is the more influential variable re: WR development.

Phenological development is directly dependent on water depth; the greater the water depth, the longer it will take a WR plant to reach the surface (Thomas and Stewart 1969). Additionally, the longer it takes for the plant to reach the surface of the water, the longer it will remain under photosynthetic and respiratory stress, decreasing its likelihood of survival. Equally as important as overall plant survival is achievement of reproductive maturity – the point at which the plant releases its (viable) seeds prior to complete senescence. The depth effect will vary with the WR stand. In most WR stands there is a depth gradient from the shore outward. Plants at the outer edges, where water is deeper, develop more slowly than WR plants in areas with shallower water. Wild rice can still be in the floating leaf stages at the outer edges while the rice near shore is flowering. Depending on the configuration of the rice stand, large sections may be adversely influenced well into the summer from increases in water depths that may not adversely influence WR in shallower water. Decreased light penetration due to increased water depths would also decrease tillering and ultimately grain yield. Bloom et al. (2001) reported yields in the same transects in Rice Lake, MN, declined > 8x from 1383 lb / acre in year 2000 to 170 lb / acre in year 2001 as average water depths increased from 26 inches (66 cm, 2.17 ft) to 43 inches (109 cm, 3.58 ft). In both years, grain yield and biomass were negatively correlated to water depth increases. Marcum and Porter (2006) reported that the number of mature seeds per panicle and total seed yield decreased in controlled experiments as depth increased from 15 – 30 cm (0.5 – 1.0 ft) to 46 – 61 cm (1.5 – 2.0 ft). No WR seedlings were able to reach the surface of the containers when planted with a water depth of 76 cm (2.5 ft). Specific examples of water depth influences on WR development from more recent experimental conditions, and open-water (field) conditions, are detailed in **Figures 1-9.**

Influences on WR from water depth increases depend on its phenology at the time of increase. If the increase is sudden during the submerged or floating leaf stage, the less developed roots may not be able to anchor the plant, which may then be uprooted (Thomas and Stewart 1969). If water depth increase is more gradual and the plant is still in the submerged stage, it will take longer to reach the surface with corresponding losses in yields due mostly to decreased tillering, or complete loss of reproductive success due to mortality. If the plant has achieved floating leaf stage and is then submerged, the plant is placed under stress since gas exchange with the atmosphere has been interrupted – NOTE: at this stage, the cuticle may have already formed further exacerbating WR plant stress due to decreased gas exchange ability while submerged. Some varieties survive by reducing growth and initiating metabolic processes that enable the plant to tolerate temporarily increased water depth. Other varieties elongate by internodal growth returning the leaves to the water surface as quickly as possible. It is likely this is the strategy used by WR. Using rafts with suspended buckets containing WR plants, Stevenson and Lee (1987) concluded that although WR was able to tolerate increases of up to 50 cm (1.64 ft), increases in water depth of 15 – 30 cm (0.5 – 1.0 ft) caused decreases in total dry weights, number of tillers, and grain yield. The more severe response to depth increases under natural conditions were attributed to decreased / decreasing nutrient levels versus the fertilized treatments in their rafts. They suggested that higher nutrient levels ensured more robust plant growth that enabled the plants to survive the water level increases. It may also be possible that the WR variety used had a genetic tolerance to depth increases such as shown by Counts and Lee (1988). As water levels increase, the plants elongate to reach the surface. If the water levels then recede, the leaves and stems are more susceptible to breakage (Thomas and Stewart 1969). Overall, although WR plants may have the ability to continue growth in cases of increased / increasing water depth, WR plant health will likely be adversely influenced resulting in decreased reproductive success, and potentially nutrient deficiencies due to the need for increased plant biomass to (re)achieve floating leaf, aerial, and seed-bearing stage(s).

Finally, consideration has to be given to the water depth during winter. If water depth decreases to an extent that the water in the rice areas freezes to or past the sediment-water interface, the seed may desiccate (essentially the same as 'freezer burn') and lose its ability to germinate. In natural stands of WR, this is commonly known as the 'ring effect' whereby no WR grows along the shallower edges of the water body, but is present in some deeper sections (Aiken et al. 1989).

1.2 Biological Influences – Competing Aquatic Vegetation

Another adverse influence in WR areas is development of problematic densities of competing aquatic plants (**Figures 1-3, 10-14**). Specific herbicides may be used to control problematic aquatic plants. Mechanical harvesting of competing vegetation has also been used as a control practice by cutting off photosynthetic organs and / or culms which supply the rhizosphere with oxygen (Lee 1986). A more substantial problem has been increased coverage of WR areas by narrow leaf cattails tolerant of similar water depths as WR. Cutting or harvesting as a cattail control method has been effective, and is currently being tested in a cattail dominated area (which was dominated by WR multiple years ago) in Ontario on the Seine River near the Minnesota border (**Figures 1-3**).

Primary factors limiting the restoration of WR in areas previously dominated by WR have been related to water depth and managing competing aquatic vegetation (see amended attachments – 'MN Conservation Volunteer – Wild Rice Renaissance,' and MPR News re: Fond du Lac Band WR restoration activities). Properly managing water depths in lakes that once contained WR has been effective. In some cases, WR seed likely remained in the seed bank due to secondary dormancy (Atkins 1983). In other cases, volunteer WR appeared in commercial amounts once competing cattails were removed with a 'cookie-cutter' (blades mounted on barge) at Long Point on Lake Erie (Lee 2001). One major restoration project was the re-establishment of southern WR into a contaminated site on Lake Ontario (Lee 2004). The site had also been invaded by carp; WR production was only possible once carp had largely been removed.

Overall, as also discussed in following sections of these comments, controlling competing vegetation in waters intended for WR production is critical for maintenance of desired WR growth, distribution, abundance, and productivity.

1.3 Major Chemical Influences

Some initial research describing WR in relation to water chemistry are Moyle's (1944; 1945; 1956) descriptions of WR in relation to water chemistry in Minnesota. Moyle suggested that WR was primarily found in waters with a total alkalinity less than 40 mg l-1, pH between 6.8 – 7.0, and a sulfate concentration of less than 10 mg l-1. It is noteworthy that these observations led to the development of Minnesota's regulation concerning the discharge of sulfates. Under the Class 4A use classification for Agriculture and Wildlife, Minnesota's water quality standard states: '10 mg / L sulfate - applicable to water used for the production of wild rice during periods when the rice may be susceptible to damage by high sulfate levels.' (Minn. R. 7050.0224, subpart 2). Moyle's observational work has led to a number of studies concerning the importance of sulfate. Paulishyn and Stewart (1970) reported WR growing in Manitoba in waters with sulfate ranging from 2 – 170 mg l-1. Rogalsky et al. (1971) advised that levels of 200 mg l-1 sulfate were acceptable for WR paddies. In a study in the Mississippi River in Minnesota, Lee and Stewart (1981) showed that WR grew well in waters with levels of 30 mg l-1 and showed that sulfate in the water varied seasonally at one sampling site from 5 – 120 mg l-1.

Controlled experiments that examine the effects of sulfate have also been conducted. The hydroponic solution recommended by Malvich and Percich (1993) uses a sulfate concentration of 48 mg l-1. Using this culture solution, Lee and Hughes (2000) found that early WR development was affected at sulfate concentrations in the range 1200 – 1500 mg l-1. Vicario and Halstead (1968) conducted experiments with rice in culture solutions with sulfate that ranged from 0 to 8800 mg l-1. They observed decreases in weight and height when sulfate in the culture solutions went above 220 mg l-1. More recent laboratory studies exposing WR seeds to various concentrations of sulfate and chloride salts under hydroponic conditions concluded that adverse influences from sulfate in particular occurred at concentrations over 1500 mg l-1 (Fort et al. 2014).

Currently, a debate has been initiated that the problem is not aqueous sulfate, but rather the production of hydrogen sulfide (H2S) in the sediment and sediment porewater related to aqueous sulfate. This was previously postulated by Grava (1973) and Grava and Rose (1975) who suggested that sulfides could form in WR paddies and adversely influence WR when sulfate was added as a fertilizer as ammonium sulfate, or an algicide as copper sulfate (Grava 1977).

Other water quality variables have also been described for waters in which WR grows. Lee (1979) in a survey of WR lakes in Minnesota and Ontario found the majority of lakes supporting WR had soft water with average alkalinities of 40 mg l-1 and pH levels of ~ 6.9. Pip (1984) examined the distribution of 59 species of aquatic macrophytes, including WR, outside and inside the Precambrian shield of central Canada. She found the more important water chemistry parameters associated with their distribution to be pH, TDS, and total alkalinity. Chloride, phosphorus, and sulfate concentrations were reported as '…of minor importance in both areas.' Wild rice is generally associated with more oligotrophic waters. Pilsbury and McGuire (2009) attributed losses of WR in Minnesota and Wisconsin to residential and agricultural developments that increased nutrient levels, which can result in increased competition from other aquatic plants including algae. Ammonia and pH changes were specifically implicated. Reduction in the range of WR has also been attributed to human disturbance including water contamination, recreational activities (boat turbulence), and importantly water level manipulation (Meeker 1996; Bennet et al. 2000). Whether eutrophication is a causative factor or correlated factor is not currently defined. Jorgenson (2013) showed that WR could grow in both eutrophic waters with seasonal total phosphorus concentrations reaching 1500 µg l-1 and non-eutrophic waters with total phosphorus concentrations of only 170 µg l-1. Finally, although WR distribution may be influenced by water chemistry or at least correlated to water chemistry, WR also affects the water chemistry in which it lives. Lee and McNaughton (2004) showed that water surrounding WR stands contained lower sulfur (S), and higher conductivity, calcium, and iron concentrations than open water areas.

Wild rice obtains most of its nutrients from the sediment. Nutrients in the rhizosphere of the WR plant are more influenced by plant growth (Jorgenson 2013). Seasonal nutrient concentrations in the WR roots seem to be correlated to those in the stems and leaves (Lee and Stewart 1983) suggesting that sediment characteristics around the roots are translocated to the rest of the plant. For commercial purposes, concentrations needed for paddy production related to fertilizer requirements are well documented (Oelke et al. 1982; Marcum 2006). These concentrations are determined using traditional soil science methods: drying and grinding, followed by analysis of filtered supernatants released with specific extracts. Day and Lee (1989) outlined methods used to classify sediments suitable for growing WR.

Their procedure was to extract nutrients from the soils while still wet and express concentrations on a volume rather than a weight basis. This procedure corrected for the variations in bulk densities observed within and between lake sediments. Other studies have used total concentrations of nutrients (requiring digestion) to describe soil characteristics (Atkins et al. 1992) or extracts on dried soils (Lee 1979). Microwave sediment digestion is the more common procedure (LUEL 2012). Sediment porewater nutrient concentrations are another method of comparing nutrient availability, but do not estimate the replenishment ability of nutrients from soil particles. There is also the question as to whether pore water concentrations determined by centrifuging samples are comparable to those obtained from 'peepers,' i.e., simple sediment porewater sampling devices. Investigations by Mayer et al. (2002) showed that pore water values obtained from 'peepers' in a highly eutrophic wetland compared well to those obtained by Lee (2001). The following ranges for parameters (mg l-1) in pore water and for uncapped total values in sediment from WR areas (**Table 1**) was developed using data from Jorgenson (2013) for a mesotrophic and eutrophic WR wetland and values for a highly eutrophic area growing WR studied by Lee (2001) and Mayer et al. (2002).

Table 1. Concentrations of sediment pore-water characteristics measured from a highly eutrophic area.

Parameter	Pore Water Range (mg l^{-1})	Total Range (µg g^{-1}) or (%)
Ca	29.1 – 150	0.8 – 4.6 %
Ba	0.057 – 0.16	47.7 – 178.0 (µg g^{-1})
Fe	0.009 – 15.0	0.54 – 2.7 (%)
K	0.11 – 5.2	0.06 – 0.90 (%)
Mg	5.3 – 34.5	0.16 – 1.3 (%)
Mn	0.001 – 1.03	107 – 555 (µg g^{-1})
P	0.003 – 7.5	0.05 – 0.15 (%)
S	0.10 – 38.5	0.45 – 1.25 (%)
Sr	0.074 – 1.2	21.5 – 136 (µg g^{-1})
NH_4	Up to 150	Total N – Up to 1.28 (%)

It is notable that there is a range of values for multiple parameters of one to three orders of magnitude suggesting that WR has a wide tolerance range of these characteristics.

Values for metals and sulfate levels in solution have been investigated using hydroponic methods by Lee and Hughes (1997) and Lee and Hughes (2000). Values listed below are for lowest observed effects for leaf and root areas in range finding experiments (**Table 2**). More recent laboratory studies exposing WR seeds under hydroponic conditions suggest that adverse responses are observed at aqueous sulfate concentrations exceeding 1500 mg / L (Fort et al. 2014).

Table 2. Lowest observed effect levels for specific elements, and sulfate, in solution from Lee and Hughes (1997; 2000)

Parameter	Lowest Observed Effect (Leaf) (mg l^{-1})	Lowest Observed Effect (Roots) (mg l^{-1})
Al	1.0	1.0
Cu	1.0	1.0
Cd	0.01	1.0
Pb	1.0	1.0
Hg	1.0	1.0
SO_4	1500	

Values for the same metals in pore water in the above publications were generally below detection levels (mg l-1): Cu (0.002); Cd (0.001); Pb (0.005). Al was reported above detection levels (0.005), with average values ranging from 0.005 – 0.012 mg l-1. All metals were therefore below levels where any adverse influence on WR should occur. In terms of sulfate, the highest values in the pore water would be approximately 120 mg l-1, below levels considered detrimental in the above studies.

2.0 WILD RICE IN MN PRAIRIE POTHOLES

The Prairie Pothole region of MN extends throughout approximately the central-western portion of MN. These bodies of water are remnants of glacial activity, are 'land-locked' (not a part of a riverine system), are fairly small re: surface area (contrasted to 'lakes' and reservoirs as would be commonly defined), and are predominantly surrounded by agricultural activity; the portion of MN in which prairie potholes are located tends to have terrestrial soils suitable for cropland. Since prairie potholes are isolated from flowing systems and are relatively small re: surface area, other than water fowl (for hunting purposes) they tend to not be managed as a resource for aquatic plants; in this case, specifically WR.

Currently, prairie potholes have been included in a debate about their suitability as water resources for WR habitat. As typically isolated water bodies surrounded by agricultural activities, potholes may not be considered optimal, or even suitable, WR habitat for multiple reasons – the two primary reasons, as the initially more important reasons, are lack of water depth control and aquatic plant management. Influences from surrounding land use patterns may also contribute to the general non-suitability of potholes as WR habitat (nutrient inputs, pesticide / herbicide exposures, localized groundwater use); however, in the absence of data supporting these claims, discussion will be limited to the primary physical (water depth) and biological (competing aquatic vegetation) influences.

2.1 PHYSICAL INFLUENCES – WATER DEPTH

Prairie potholes in MN as described above are unlikely water resources capable of sustaining perpetual, harvestable densities of WR due to their typical non-management of water depth, arguably the more important characteristic of WR waters requiring management for a sustainable WR population. Standing water presence and absence, and levels in the case of presence, in potholes can be hydrologically influenced by localized groundwater levels, as well as precipitation events. Due to weather-related and overall climatic influences, acceptable WR habitat may not be available in specific potholes, or entire regions of potholes; periodic years lacking standing water, with contrasting periodic years of increased standing water depth can result in depletion of any viable WR seeds that may have been present in the pothole sediments. This depletion of any viable WR seeds would presumably occur under the following scenario – during years of increased water depth, (viable) WR seeds may germinate, but not have the ability to achieve reproductive success due to excessive water depth. A visual example of how this scenario may influence WR abundance may be inferred via **Figures 4-9, 13-16**. **Figures 4-9** are pf rafts used to specifically test influences of water depth on WR plant germination, growth, and development; and the general area surrounding the rafts. **Figures 13-16** are of prairie potholes, which historically have been observed without standing water.

In general, in the absence of water depth control and maintenance of a preferable WR water depth, and the almost ephemeral nature of prairie potholes re: presence / absence of standing water, prairie potholes are unlikely to be acceptable habitat for WR production, regardless of chemical characteristics of overlying water, sediment, and sediment porewater.

2.2 Biological Influences – Competing Vegetation

As previously mentioned, prairie potholes are not typically managed for WR productivity; specifically, in terms of maintaining stable and appropriate water depth, and management of aquatic vegetation which may complete with, and out-compete, WR for scarce resources – of particular interest is light availability. Adverse influences from aquatic vegetation competing with WR for scarce resources can be exacerbated in the presence of non-controlled water depth. Under conditions of water depth in excess of optimal WR conditions (0.5-3.0 feet), competition for scarce resources such as light can decrease the rate of development and overall potential for achieving reproductive success. Continued occurrence of WR seed germination followed by lack of reproductive success can result in depletion of the viable WR seed source. Examples of a lake and pothole, respectively, in which competing aquatic vegetation may be a hinderance to WR abundance are included as **Figures 10-16**. Additionally, in the event that a prairie pothole 'dries up,' the area which would have been considered aquatic may become dominated by terrestrial plants. This further decreases the likelihood that a prairie pothole exhibiting this hydrological scenario is acceptable habitat for WR production.

Overall, prairie potholes are not generally controlled, or controllable, for WR production. Reference of prairie potholes as poor WR habitat specifically due to chemical characteristics that may be detrimental to (WR) growth is incomplete, and not necessarily defensible if not considering the variable hydrological cycle(s) of any specific pothole.

3.0 Water Lilies as an Indicator of Acceptable Wild Rice Habitat

3.1 Physical Influences

Several examples exist of aquatic plants, both rooted and non-rooted, which can occur in areas of aquatic systems with conditions favorable for WR plants. Currently, water lilies (lily pads; *Nymphaea odorata*)) have been suggested as an indicator of acceptable WR habitat in aquatic systems; although, water lilies can also grow in areas lacking preferential conditions for WR – specifically, water lilies can grow in water sufficiently deep to be counter-productive to WR abundance. Although water lilies can occur in the same general area as WR, and in some cases, co-occur, competing vegetation in general adversely influences the abundance of WR.

One particular WR water this association may be observed is Lake Monongalia in Kandiyohi County, MN, a large and shallow water body on the Middle Fork of the Crow River north of New London, MN (**Figure 10**). In this image, both WR and water lilies can be observed in the same general area; however, there appears to be a distinction between populations of each plant; and although some water lilies occur within the WR areas, a separation between higher densities of each plant appears to be evident. In addition to the image provided as **Figure 10**, additional images of near-shore WR areas with associated water lily areas are available.

Furthermore, some areas nearer shore tend to be dominated by water lilies; although water nearer shore tends to be shallower, which is preferred for WR growth and abundance. Water lilies can therefore be indicators of acceptable habitat for WR; however, in this system, in this area, a separation of higher densities of lilies and WR appears evident. For multiple reasons such as competition for resources and potential allelopathic influences, the overall inference from this observation may contraindicate water lilies as indicators of acceptable WR habitat. Elakovich and Wooten (1989) observed that the extract from fragrant water lily leaves and petioles was the more inhibitory extract in both tested assays – lettuce seedling and common duckweed bioassays. Compounds present in fragrant water lily leaves and petioles may have an inhibitory influence on surrounding aquatic plants such as WR. This allelopathic possibility was also theorized by Lee and McNaughton (2004) re: measured differences in water column chemical characteristics in areas dominated by water lilies. Quayyum et al. (1999) observed significant decreases in WR seedling root and shoot lengths following exposure to water lily rhizome extracts. These observations suggest the distinct possibility that water lilies may have an inhibitory influence on WR health and abundance; likely more so in areas of water lily dominance; potentially supported with field observations such as that in **Figure 10**. Furthermore, due to these observations, the potential exists for legacy inhibitory influences on WR from water lily degradation in aquatic sediments.

The observation of apparent separation of water lilies and WR may also be an example of 'ring effect' as described in section 2.1. However, if this is the case nearer-shore habitat may not be suitable for WR growth due to the likelihood of seed desiccation during winter. Additionally, water lilies have been observed to grow in areas of this system with water depths exceeding three feet – a depth not conducive to WR plant growth. In a system with non-controlled water depth, water lilies may be a high proportion of the aquatic plant assemblage in the absence of WR. This could also be due to a lack of viable WR seed in the sediment; a potential result of WR germination in excessive water depths without subsequent reproductive success.

In this particular area, WR and water lilies do occur in the same general area; however, a distinction between higher density populations of each plant appears evident. Due to this observation and the scenarios detailed above, simply stating that the presence of water lilies is an indicator of acceptable WR habitat is overgeneralized.

4.0 Might the 120 µg / L Sulfide Protective Level Improve WR Distribution in MN?

A component of the current debate about developing site-specific standards for sulfate in discharge waters is application of a sediment porewater sulfide protective level of 120 µg / L, which may improve WR distribution in MN. Although as a general rule sulfide as hydrogen sulfide (H2S) can be problematic to organisms, there is a tolerance range associated with what may be the exposure concentration at which adverse responses are observed – WR in this case is no exception. Based on current MPCA field data and observations, WR can grow to a density of > 100 stems per square meter in the presence of hydrogen sulfide concentrations exceeding 120 µg / L. The degree of variability of WR presence and density in areas of pore water sulfide concentrations exceeding 120 µg / L increases doubt whether the 120 µg / L H2S protective level would measurably benefit WR under field conditions; or whether that particular H2S concentration would persist over multiple growing seasons.

Based on available data, and consideration of biological, physical, and other environmental influences beyond control specific to microbial H2S synthesis, application and enforcement of a sediment porewater sulfide WR protective level is unlikely to be beneficial to WR distribution in MN.

4.1 Physical Influences – Water Depth

As described multiple times previously, water depth should be one of the first, if not the first, consideration(s) when determining acceptable aquatic habitat for WR growth and abundance. The synthesis of hydrogen sulfide (H2S) in sediment porewater is dependent on the absence of oxygen in the area of H2S generation. In general, shallower water preferred by WR is more easily mixed during disturbance events, and therefore the likelihood of oxygenating the entire water column increases as water depth decreases. Since water depth is a primary controlling factor for WR distribution and abundance, and WR tends to prefer shallower water (0.5-3.0 feet deep), the likelihood of oxygenating the entire water column in areas of preferential WR habitat specifically during disturbance events would likely be high. Therefore, one controlling factor for hydrogen sulfide synthesis in nearer-surface sediments is likely water column oxygenation, both duration and frequency; in addition, sufficiently intense disturbance events could disrupt nearer-surface sediments, resulting in oxygenation of the disturbed sediment area and decreasing H2S synthesis potential.

Microbial metabolic rate can also be controlled by temperature of the surrounding medium; as a general rule, as the temperature decreases, microbial metabolic rate decreases, which can influence H2S synthesis. Factors associated with microbial synthesis of H2S are unlikely to be predictable due to factors beyond control – temperature fluctuations; precipitation event frequency, duration, and intensity; and the actual density of microbes capable of H2S synthesis. These influences would likely become more intense during different seasons; specifically, late-Spring / early-Summer during snow-melt, and more extreme weather events during seasonal transition, which, as suggested above, are more likely to result in whole water-column oxygenation, potentially decreasing H2S production in near-sediment surface pore water.

4.2 Biological Influences –Aquatic Plants – Wild Rice

Wild rice has the capability to oxygenate its root zone (aka rhizosphere) through a process known as radial oxygen loss (ROL), thus resulting in more chemically oxidizing conditions in the area immediately surrounding, and in contact with, its roots. ROL can be a controlling influence on the presence of chemically reduced elements and compounds, one of which is H2S. As WR typically germinates during late-spring, water column oxygenation and oxygen-carrying capacity due to mixing influences (spring melt, temperature changes, storm events) tends to be higher, which can be a limiting factor for H2S synthesis in nearer-surface sediments. As WR plants mature, their ability and extent of maintaining ROL increases and may decrease the likelihood of adverse influences from reduced chemical species (i.e., H2S) on WR health, abundance, and distribution.

In addition to influences on H2S synthesis via ROL by WR, since H2S synthesis is driven via microbial activity, maintenance of an appropriate type and density of sulfur / sulfate reducing microbes is necessary for H2S synthesis. ROL from WR plants could influence the overall composition of the microbial assemblage, further decreasing the potential for microbially mediated H2S synthesis during periods of growth for WR plants.

5.0 Potential Influences from Iron Plaque Formation on Wild Rice Roots

As previously referenced, WR plants can release oxygen into the rhizosphere through a process known as radial oxygen loss (ROL) promoting more chemically oxidizing conditions in the rhizosphere. This can aid in protecting the roots from chemically reduced elements and compounds, such as ferrous iron (Fe2+) and hydrogen sulfide (H2S). Under certain conditions, iron can precipitate onto root tissue as oxidized iron (iron oxy-hydroxides), or reduced iron (iron sulfide). Oxidized iron precipitates on root tissue have been observed to occur during the plant's life stage(s) in which growth is the more dominant activity. Reduced iron precipitates have been observed to occur during the plant's life stage in which reproduction is the more dominant activity; during this time the seed is maturing, while the remaining portions of the plant are beginning to senesce. Precipitation of reduced iron species could be expected, since plant senescence during seed maturation involves decreased energy allocation to maintaining the shoot, stems, and leaves, and the likely decreased rate of ROL into the rhizosphere. Regardless of the speciation of iron, these precipitates have been commonly referred to as 'iron plaques.'

A proposed mechanism of iron plaque formation is detailed in Jorgenson (2013), and potential influences on plant physiology and reproduction in terms of nitrogen uptake and translocation is detailed in LaFond-Hudson (2016). The general suggestion is that iron plaque formation on roots of WR plants exposed to increased aqueous sulfate is a potential source of decreased nitrogen content of WR seeds produced by exposed plants. Although a lower nitrogen content of WR seeds may suggest a less 'healthy' seed, additional generational research is required to investigate influences on germination of viable WR seeds from plants exposed to increased aqueous sulfate, with generally decreased seed nitrogen. Since this was an observed association under more controlled laboratory conditions, field verification of these observations would be required to allow a more applied perspective to these data.

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FIGURES

Figure 1. 2014-08-24_Year of water ≥ 3 feet deeper during spring / early-summer during critical seedling phenological stage. Area of cattail removal as 'pathway' to island. **NOTE**: Absence of WR plants in cattail removal area, and open water outside cattail area. **WATER DEPTH / CLARITY, COMPETING VEG., VIABLE SEDIMENT SEED SOURCE.**

Figure 2. 2015-08-03_Year of more typical water depth (~ 1.5 – 2.0 feet) throughout WR growing season. **NOTE**: WR in open water area; 'lighter green' WR in area of cattail removal; potential nitrogen deficiency. **WATER DEPTH / CLARITY, COMPETING VEG., VIABLE SEDIMENT SEED SOURCE.**

Figure 3. Year of typical water depth throughout the WR growing season. Closer view of WR plants in cattail removal area. NOTE lighter green coloration of plants; potential nitrogen deficiency. **WATER DEPTH / CLARITY, COMPETING VEG., VIABLE SEDIMENT SEED SOURCE**.

Figure 4. 2014-08-23_40 cm (~ 1.3 feet) below water surface. **NOTE**: Most all plants achieved reproductive maturity. **WATER DEPTH / CLARITY, COMPETING VEG., REPRODUCTIVE MATURITY.**

Figure 5. 2014-08-23_110 cm (~ 3.6 feet) below water surface. NOTE: No viewable plants from surface. **WATER DEPTH / CLARITY, COMPETING VEG., REPRODUCTIVE MATURITY, NO SEED PRODUCED FOR FOLLOWING SEASON.**

Figure 6. 2014-08-23_110 cm (~ 3.6 feet) below water surface. NOTE: No viewable plants from surface. **WATER DEPTH / CLARITY, COMPETING VEG., REPRODUCTIVE MATURITY, NO SEED PRODUCED FOR FOLLOWING SEASON.**

Figure 7. 2014-07-18_Field deployment location for water depth study. NOTE: No WR plants observed along periphery of raft deployment location – contrast to **Figures 8 and 9**. Water depth multiple feet deeper along periphery of channel during spring / summer 2014. **WATER DEPTH / CLARITY, COMPETING VEG., REPRODUCTIVE MATURITY.**

Figure 8. 2015-07-22_WR water depth study raft deployment location. NOTE: WR plants throughout periphery of deployment location; general absence of competing vegetation. Water depth multiple feet shallower during spring / early-summer 2015. Water depth in WR areas < 2.0 feet. **WATER DEPTH / CLARITY, COMPETING VEG., VIABLE SEDIMENT SEED SOURCE, REPRODUCTIVE MATURITY.**

Figure 9. 2015-07-22_ WR water depth study raft deployment location. NOTE: WR plants throughout periphery of deployment location; general lack of competing vegetation. Water depth multiple feet shallower during spring / early-summer 2015. Facing opposite direction as **Figure 8**. **Figure 7** vantage point at bend in river channel in background. Water depth in WR areas < 2.0 feet.

Figure 10. Lk. Monongalia WR and water lilies. **NOTE**: Although they are in the same 'area,' tend to display clumped dispersion pattern; a distinction between higher densities of each plant appears evident. This 'separation' was observed in multiple locations. Additional pics available on request. **WATER DEPTH / CLARITY, COMPETING VEG., POSSIBLE ALLELOPATHY, REPROD. MATURITY, VIABLE SEDIMENT SEED SOURCE.**

Figure 11. Prairie pothole east side of Hwy 71. Have not observed without standing water. NOTE: Dense competing vegetation along shoreline in area more likely to be preferable for WR growth. **WATER DEPTH NOT CONTROLLED, PERIODICALLY DRY (?), COMPETING VEG. (ROOTED, POSSIBLE ALGAL COMPETITION), POSSIBLE ALLELOPATHY, UNLIKELY VIABLE SEED IN SEDIMENT, HERBIVORY.**

Figure 12. Prairie pothole west side of Hwy 71. Have not observed without standing water. NOTE: Dense competing vegetation along shoreline in area more likely to be preferable for WR growth. **WATER DEPTH NOT CONTROLLED, PERIODICALLY DRY (?), COMPETING VEG. (ROOTED, POSSIBLE ALGAL COMPETITION), POSSIBLE ALLELOPATHY, UNLIKELY VIABLE SEED IN SEDIMENT, HERBIVORY.**

Figure 13. Prairie pothole south of Spicer on Hwy 23. Have observed without standing water. NOTE: Current density of duck weed and possible other algal taxa - competing vegetation. **WATER DEPTH NOT CONTROLLED, PERIODICALLY DRY, UNLIKELY VIABLE SEED IN SEDIMENT, COMPETING VEGETATION – LIGHT LIMITING.**

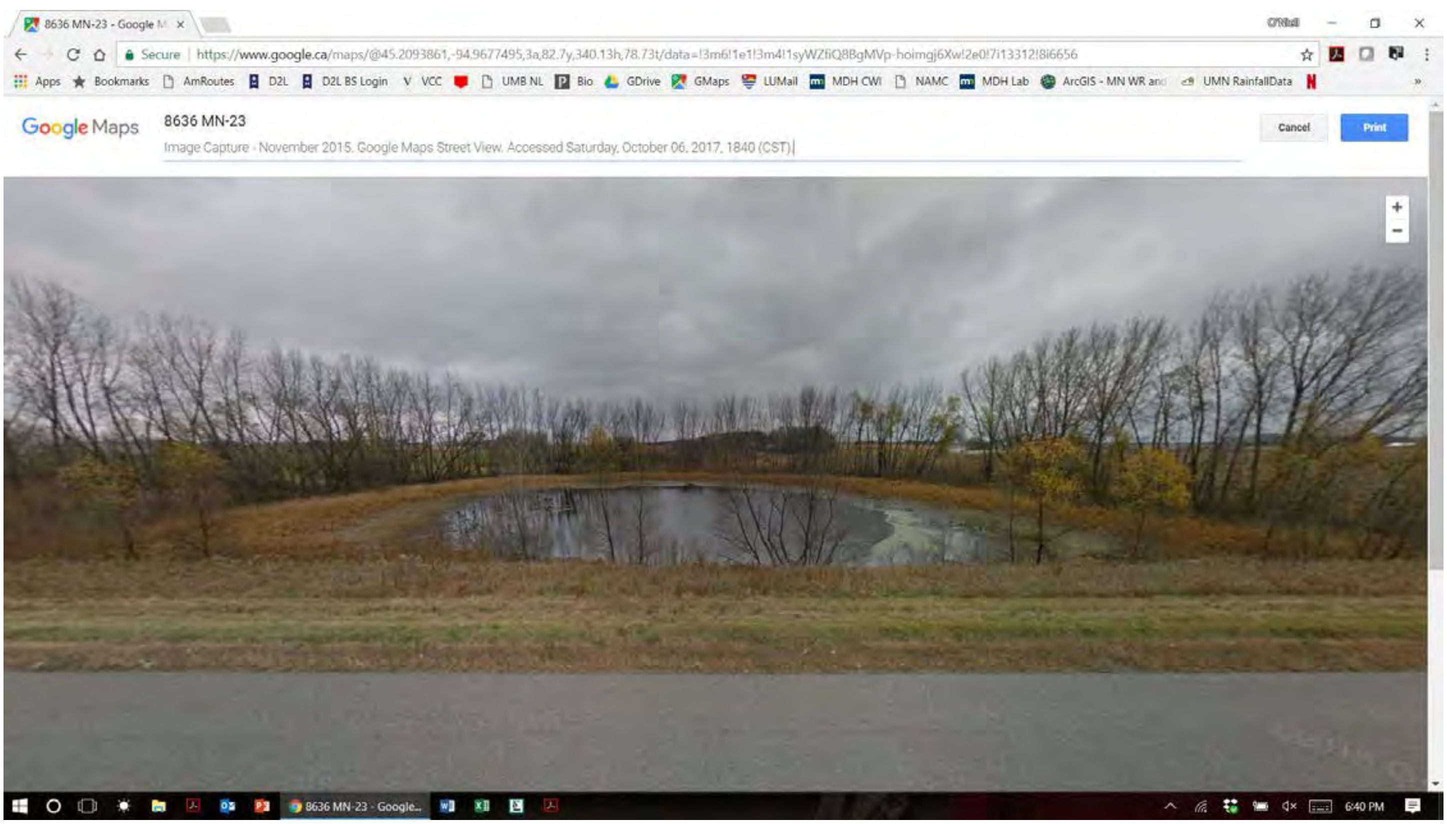


Figure 14 (same 'pothole' as Figure 13). Image capture by Google Street View - November 2015. NOTE: Low water level. This 'pothole' has been observed without standing water.

Figure 15. Prairie pothole west side of Hwy 71. Have observed without standing water. NOTE: Dense competing vegetation along shoreline in area more likely to be preferable for WR growth. **WATER DEPTH NOT CONTROLLED, PERIODICALLY DRY, UNLIKELY VIABLE SEED IN SEDIMENT, HERBIVORY.**

Figure 16. Close-up of distant area of **Figure 13**. Have observed without standing water. **WATER DEPTH NOT CONTROLLED, PERIODICALLY DRY, UNLIKELY VIABLE SEED IN SEDIMENT, HERBIVORY.**

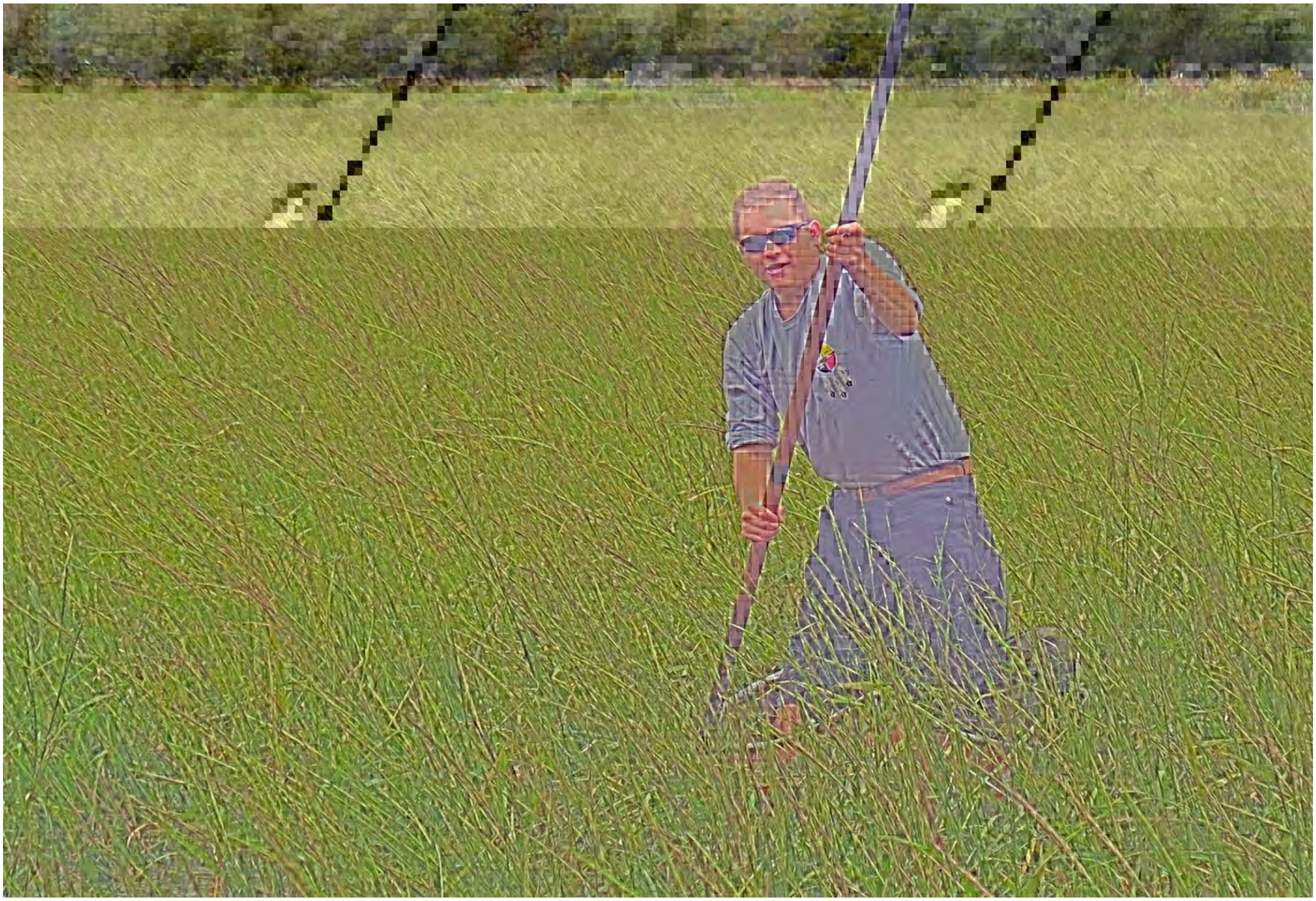
MINNESOTA PUBLIC RADIO (MPR) ARTICLE:

FOND DU LAC BAND OF OJIBWE WILD RICE MANAGEMENT

MPRnews

Fond du Lac Band restores wild rice to keep harvest tradition alive

Dan Kraker · Fond du Lac Reservation · Sep 25, 2017 Environment



His canoe almost completely hidden in wild rice, Bruce Martineau poles to the shore of Deadfish Lake on Sept. 5, 2017 Dan Kraker | MPR News

LISTEN **Story audio**

4min 14sec (https://www.mprnews.org/listen?name=/minnesota/news/features/2017/09/25/170925_kraker_20170925_64.mp3)

On the shore of Deadfish Lake on the reservation of the Fond du Lac Band of Lake Superior Chippewa earlier this month, Ed Jaakola and Jerrad Ojibway scooped handfuls of wild rice from the bottom of their canoe into big plastic bags.

The rice was tough to harvest because of the wind, Jaakola said. Still, he estimated they had gathered 80 pounds, enough to cover the bottom of their canoe. It's a tradition the 58-year-old has carried on for as long as he can remember.

"Probably 45 years for me," he said.

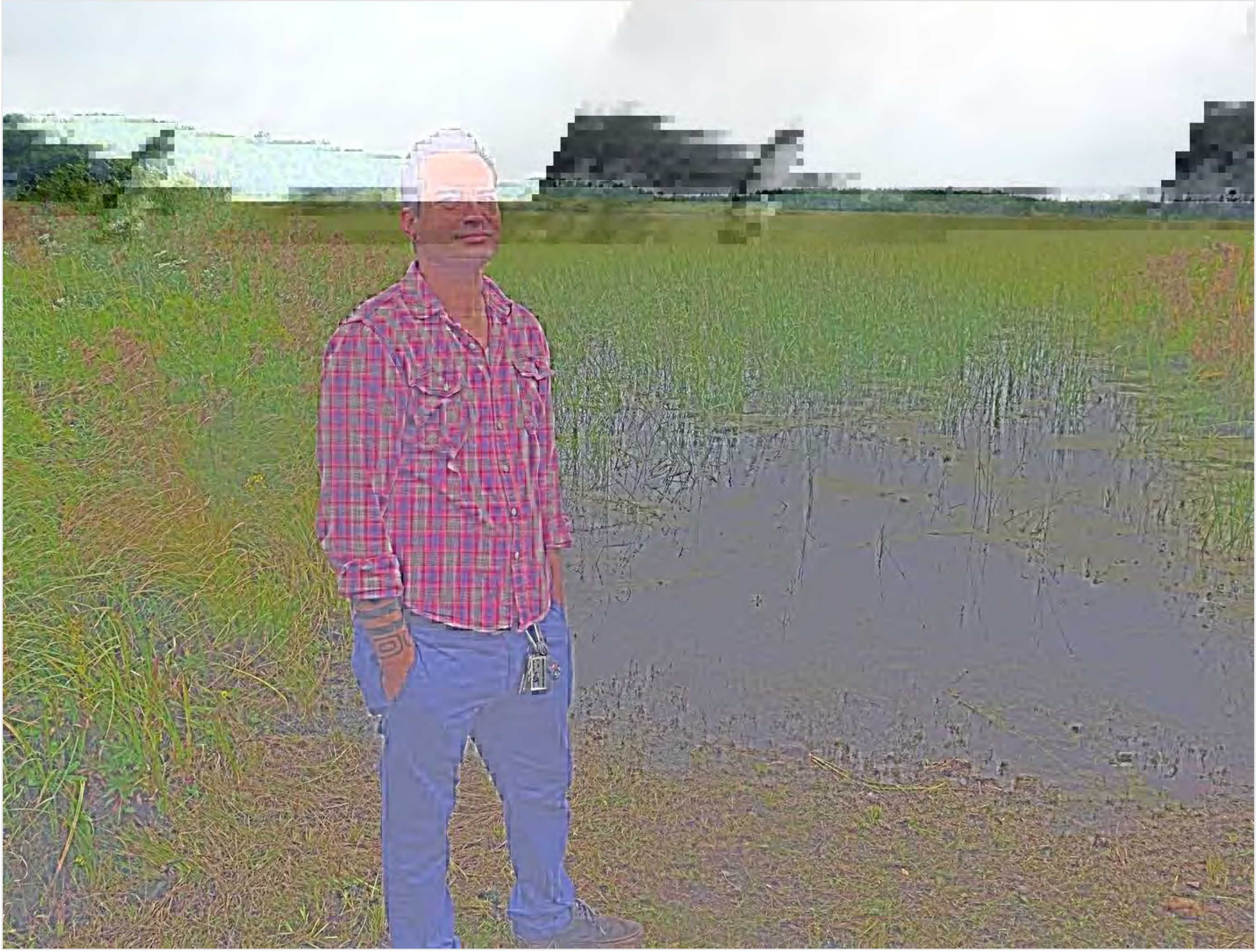
Jerrad Ojibway and Ed Jaakola bag about 80 pounds of wild rice they harvested. Dan Kraker | MPR News

Deadfish Lake, Zhaaganaashiins Odabiwining in the Ojibwe language, is blanketed so thick with wild rice this time of year it doesn't even look like a lake.

"Because you essentially don't see water when you're looking at this," said Thomas Howes, natural resources manager for the Fond du Lac Band, "you see what essentially looks like a field of grasses."

- **Appetites: The wild rice harvest is on (https://www.mprnews.org/story/2017/09/20/appetites-wild-rice-harvest-beth-dooley)**

The 100-acre lake is one of five primary wild rice lakes the band maintains. Together, they provide nearly 900 acres of wild rice habitat.



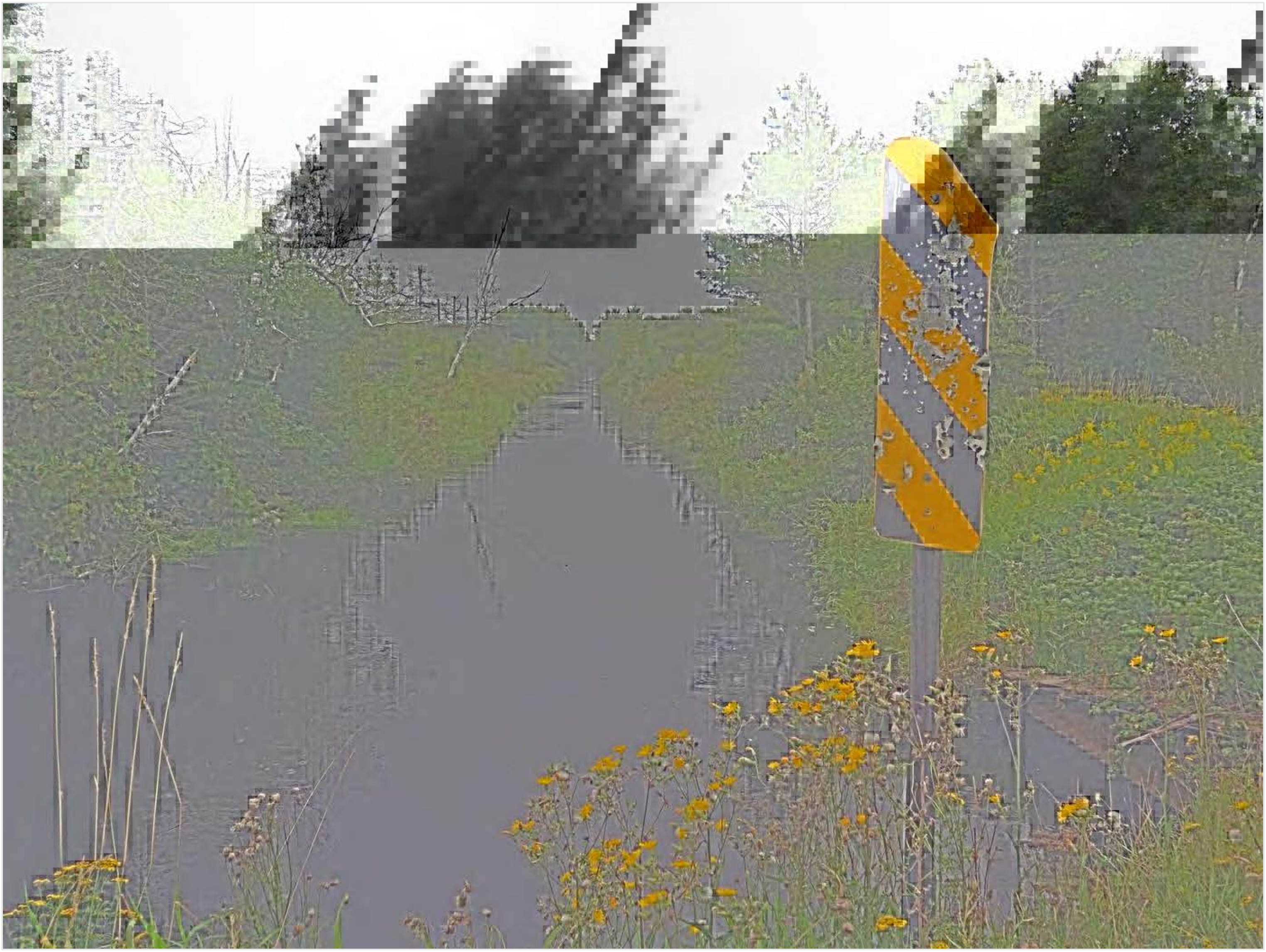
Fond du Lac Band of Lake Superior Chippewa natural resources manager Thomas Howes stands at the canoe landing at Deadfish Lake. Dan Kraker | MPR News

Deadfish Lake is especially important. "We keep it reserved for elder ricers for the first couple weeks of the year," Howes explained, "because of its ease of access, but also because now it's a reliable producer of wild rice."

But that wasn't the case more than 20 years ago. Back then, there wasn't much wild rice left on the reservation to harvest. In the early 1900s the government built a network of ditches to try to drain the land for farming.

The canals are 20 feet wide in some places. And they had an unintended consequence. They disrupted the complex hydrology of the wild rice lakes. Many stopped producing rice regularly.

"This particular lake, before 20 years ago, rice like this wasn't very common," Howes said. "So you'd have rice here once every six, eight years. You'd have to get lucky with the weather."



Drainage ditches like this one on the Fond du Lac Reservation, shown here on Sept. 5, 2017, were dug in the 1900s to make the land more suitable for farming. Dan Kraker | MPR News

And to the Fond du Lac Band, this was a loss of much more than a simple food source. Wild rice holds special cultural significance to the Fond du Lac and other Ojibwe bands.

"We came here from the East Coast of the U.S., and were told we'd find our permanent home when we found this wild rice, this "manoomin," this food, that grows out of the water," said Howes. "And that's held to be true."

So in the late 1990s the band began experimenting, to try to make the rice grow like it used to. At Deadfish Lake, they put in a holding pond above the lake and a water control structure at the outlet. The idea was to try to mimic the hydrology before all the canals were put in.

"And that's really seemed to work. Now, what we see, for the last 20 years, rice is essentially here almost every year," Howes said.

In other lakes they've had to clear out aquatic vegetation that's crowded out the rice. First, they flooded the lakes. Then they rigged up drag bars and cutting tools on the back of a big airboat to uproot the vegetation and shear it if it grew back.

· Protecting wild rice: Officials suggest new sulfate rule (https://www.mprnews.org/story/2017/08/21/to-protect-wild-rice-officials-suggest-new-sulfate-rule-)

They drilled sediment cores to see if there was still a wild rice seedbank. If there wasn't, they brought seed in from elsewhere to reseed wild rice.

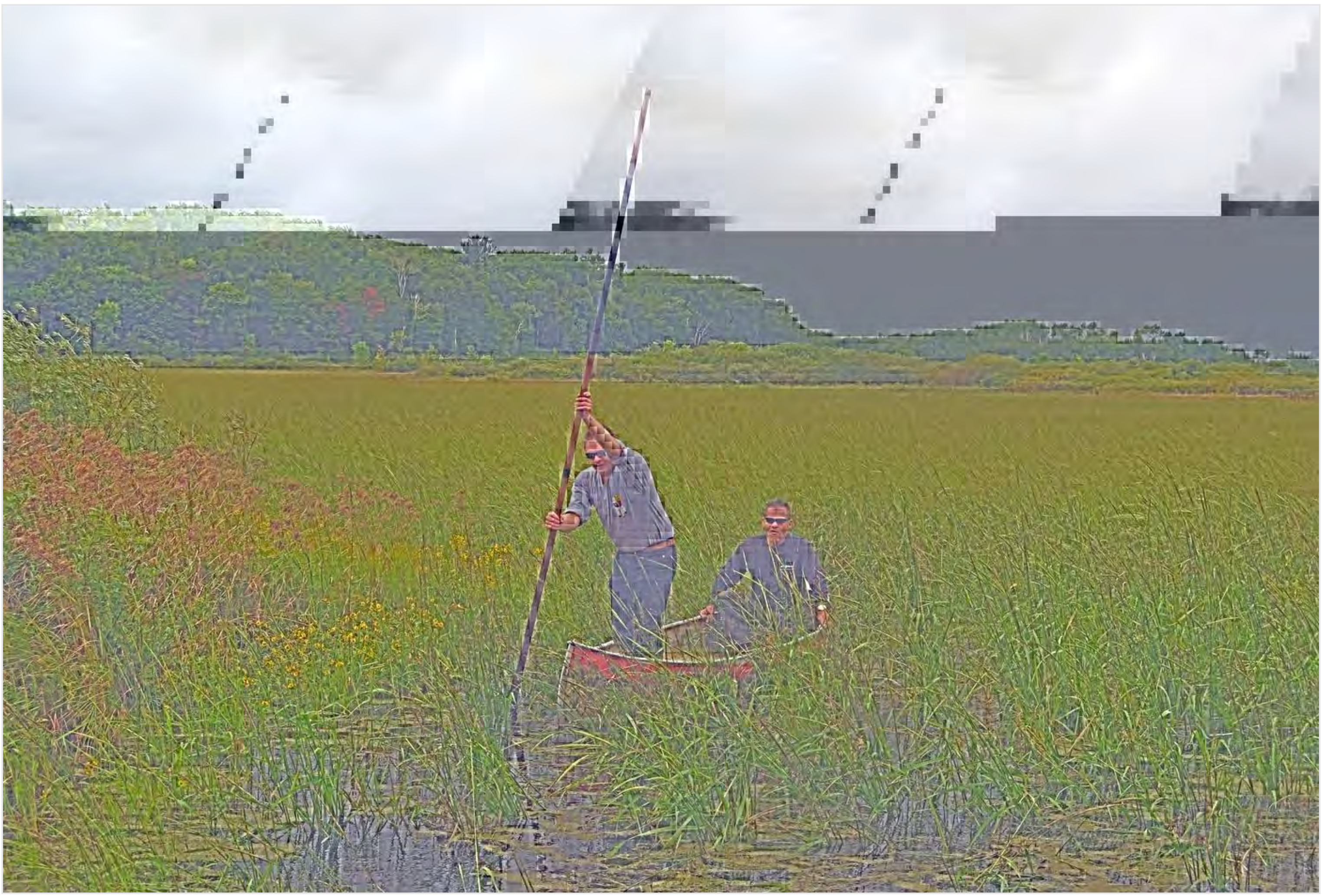
And now the rice has returned to the waters that Howes says drew the band here in the first place. Howes said he took his teenage son to a reservation lake called Mud Lake the first year rice returned.

"It was beautiful, it really was," he said. "And now he still wants to rice because of that."

The band has shared its expertise to help restore wild rice in Michigan and Wisconsin, and nearby on the St. Louis River estuary. (https://www.mprnews.org/story/2016/09/21/wild-rice-comeback-effort-st-louis-river)

Still, some tribal members complain that young people are not doing enough to keep the wild rice harvesting tradition alive.

"The younger ones, they're all on Facebook somewhere," said Jerrad Ojibwe. "They're afraid of bugs, afraid of the water," he said.



Twenty-year-old Bruce Martineau poles his father Francis Martineau to the shore of Deadfish Lake after harvesting wild rice on Sept. 5, 2017. Dan Kraker | MPR News

But later in the afternoon one final canoe pulled in to the landing at Deadfish Lake.

Twenty-year-old Bruce Martineau steered the canoe to shore with a long wooden pole. His father, Francis Martineau, sat in the bow.

The younger Martineau heaved the canoe on to shore, the bottom of the boat covered with rice. His grandfather first taught him to rice five years ago, he said.

"It's my culture," he explained. "Natives have done it since the beginning of time."

Bruce Martineau scoops up wild rice from the bottom of his canoe after harvesting the rice from Deadfish Lake. Dan Kraker | MPR News

"It's what brought us here," his father Francis added. "The food that grows on the water."

He said he's proud of his son for doing his part to keep the tradition alive, especially now that wild rice has made a comeback on the reservation.

Bruce Martineau said he hopes to print up some business cards and try to sell rice to restaurants.

But he also plans to give some away.

"God gives this, so it's only right to give it back," he said. "Give it to other people that can't go out there."

Editor's note (Sept. 25, 2017): An earlier version of this story indicated ditches on the reservation were dug for irrigation. To clarify, they were dug for drainage.

MN DNR, MINNESOTA CONSERVATION VOLUNTEER ARTICLE:

'WILD RICE RENAISSANCE'

Wild Rice Renaissance

Centuries ago, prophecies guided the Ojibwe people to migrate west to find the food that grows on the water. Mille Lacs was one of the places they stopped, around A.D. 1750, where the bays and outlet lakes were thick with the wild rice they called manoomin. For millennia before that, the Mdewakanton Dakota harvested wild rice here. Its abundance helped sustain a group of villages around Ogechie Lake, in the heart of what is now Mille Lacs Kathio State Park. By the late 1980s, however, the rice in Ogechie was nearly gone. Now, thanks to a cooperative project by the Mille Lacs Band of Ojibwe and the Minnesota Department of Natural Resources, wild rice is returning, and with it a connection to the park's ancient history.

Article continues below sidebar

A dam built in the 1930s cause wild rice on Ogechie Lake to decline, but a new outlet structure upstream at Mille Lacs has lowered Ogechie's water level and allowed for a return of this once-abundant wild grain.

The key to Ogechie's wild rice restoration was a modification to Buck Moore Dam at the Rum River outlet of the lake. Built in the drought years of the 1930s to keep water in the lake, the dam ultimately raised water levels too high for wild rice to grow. Recently, rice returned to Lake Onamia—downstream from Ogechie—after the dam there was changed to lower the water and allow old rice grains on the lake bottom to sprout.

Ogechie was trickier, because its dam also controlled the water level of Mille Lacs itself. The Mille Lacs Band of Ojibwe solved that problem by building a new control structure at the outlet of Mille Lacs. Then the old dam was modified, and, as in Onamia, rice emerged on its own.

The projects at Onamia and Ogechie are parts of a restoration initiative that benefits people and wildlife alike, according to Perry Bunting, director of environmental programs for the Mille Lacs Band's Department of Natural Resources. He says that Ogechie's rice "grew in like a green carpet" in a dramatic reappearance before being disrupted by an early summer storm. Harvesting has not been permitted yet, Bunting says, to allow the rice beds to reseed. In the meantime, paddlers benefit from the project because watercraft can now pass over the modified dam between Ogechie and the Rum River without portaging.

The Interpretive Center at Mille Lacs Kathio State Park overlooks Ogechie and is well positioned for observing the lake and wildlife. Park visitors can use high-powered binoculars at the picture window, says park naturalist Erin Fallon, or venture closer to the action: The archaeological sites on the Landmark Trail are great viewing spots. The rice will provide important feeding, resting, and staging areas for waterfowl, Fallon says, along with enhanced habitat for fish, turtles, and mammals such as muskrats.

The outlet lakes of Mille Lacs are the heart of the Kathio National Historic Landmark. One of only 25 in Minnesota, the landmark commemorates the ancestry of the Dakota Nation. It was built on a foundation of wild rice, as seen in archaeological evidence of parching, threshing, and storing.

Years ago, during an autumn archaeological dig at one of the Ogechie village sites on the Landmark Trail, I marveled at the sights and sounds of migrating waterfowl as flocks filled the open water. Now, that same view is punctuated with fuzzy green stalks, some in small clumps, others forming thick beds across portions of the lake. The upper half of Ogechie is filling in with wild rice. In Ogechie Lake, food once again grows on the water, and an ancient cultural landscape has been renewed.

David Mather, freelance writer

DEPARTMENT OF NATURAL RESOURCES

RAMBOLL ENVIRON

ENVIRONMENT
& HEALTH

Comments on: The Proposed Amendment of the Sulfate Water Quality Standard Applicable to Wild Rice and Identification of Wild Rice Waters.

OAH Docket NO. 80-9003-34519,
Revisor NO. RD4324A
November 21, 2017

Comments by: Michael J Bock, PhD on behalf of the Iron Mining Association of Minnesota

Comments addressing: (1) Derivation of a porewater sulfide threshold, and
(2) Use of an equation to derive a sulfate standard

I am a professional environmental scientist and Senior Managing Consultant at Ramboll Environ. I have more than 20 years of professional experience in environmental science and statistical analysis. My educational background is in biogeochemistry, biological science, data analysis, and statistics. I hold a PhD in Oceanography from the University of Delaware. I am proving this written testimony to support and expand on the oral testimony I provided on the 23rd of October in St Paul.

My testimony addresses two aspects of the proposed sulfate rule (RULE 7.20-7.26) that are lacking in reasonableness and scientific basis: (1) the use of 120 microgram per liter (µg/l) as a porewater sulfide threshold value for the protection of wild rice (Rule 7.20; SONAR part 6E), and (2) the use of the MPCA equation to predict a waterbody specific sulfate standard based on sediment total organic carbon (TOC) and iron and the sulfide threshold (Rule 7.26-8.2; SONAR 6E p75-77)

Specifically, in my judgement the field data does not support a porewater sulfide threshold of 120 µg/l as a reasonable sulfide threshold due to deficiencies in the raw data and statistical analyses used to derive this value. A higher sulfide threshold is predicted by statistical analyses to be as protective as the 120 µg/l value. Furthermore, the equation used to translate the sulfide threshold to a surface water sulfate threshold does not provide reasonable predictions of the sulfate threshold and yields results that are often illogical and inconsistent with MPCAs conceptual model of the interaction between sulfate and sulfide.

SULFIDE THRESHOLD COMMENTS (RULE 7.20; SONAR PART 6E)

Reasonableness of the proposed sulfide threshold of 120 µg/l

An examination of the field data used by MPCA to support the rulemaking shows that there are a great many waterbodies in the MPCA dataset that exhibit porewater sulfide concentrations that exceed the MPCA proposed threshold (>120 µg/l) and also possess healthy stands of wild rice (Figure 1 and Figure 2). This finding calls into question the validity of MPCA threshold and suggests problems and deficiencies in how MPCA used the field data to derive a threshold. As MPCA has observed, the field data provides a useful dataset for assessing the potential influence of porewater sulfide on wild rice which can be supplemented by the laboratory mesocosms and hydroponics data. A discussion of the deficiencies in the MPCA sponsored hydroponics and mesocosm studies is beyond the scope of my comments but will be addressed by others. During my technical review of the data and analyses I identified and, when possible, corrected the deficiencies in the analyses conducted by MPCA. I describe my own derivation of a conservative sulfide threshold based on the field data. Based on my analyses, the conservative sulfide threshold I derived is as protective of wild rice health as the 120 µg/l MPCA standard.

Figure 1. Presence of Wild Rice versus Porewater Sulfide Concentration

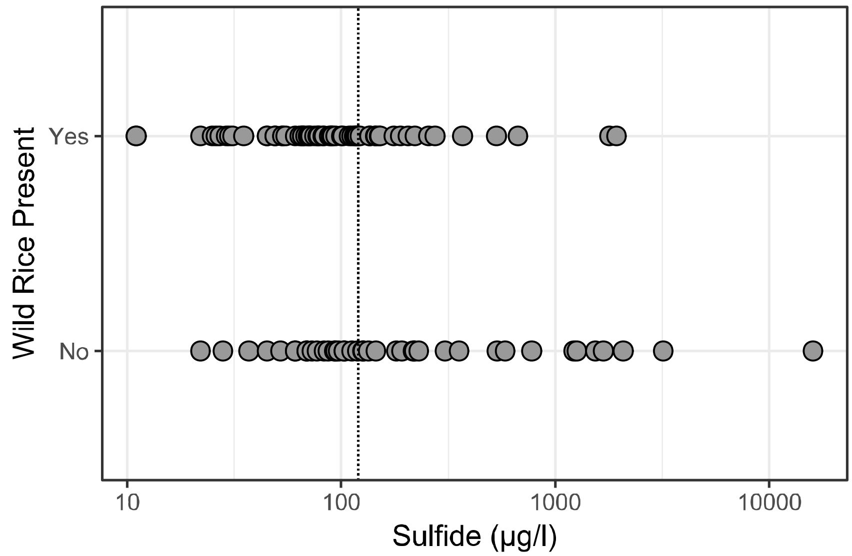
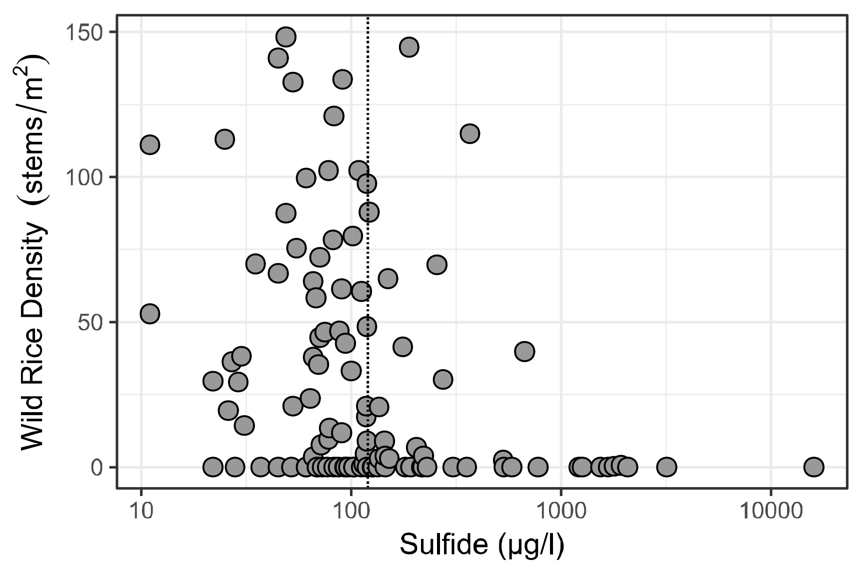


Figure 2. Wild Rice Stem Density versus Porewater Sulfide Concentration



Representativeness of the Field Data used by MPCA

MPCA generated a field dataset as part of the derivation of a new sulfate standard. Wild rice is known to be sensitive to a variety of factors unrelated to sulfide (e.g. water depth, winter temperature, the presence of competing species (TSD pages 27-28)). The field data used in MPCA's analysis was collected in 2012 (n=83) and 2013 (n=25). Significant flooding was reported in the Duluth region in 2012. This flooding occurred in June, a critical time for the germination of wild rice. MPCA did not discuss the possible importance of this flooding on in the 2012 data and the derivation of the sulfide threshold. In fact, more than 75% of the 25 samples with porewater sulfide between 100 µg/l and 150 µg/l were collected in 2012, the samples expected to have the most influence on the MPCA's 120 µg/l threshold. The potential biases associated with these data points has not been addresses by MPCA.

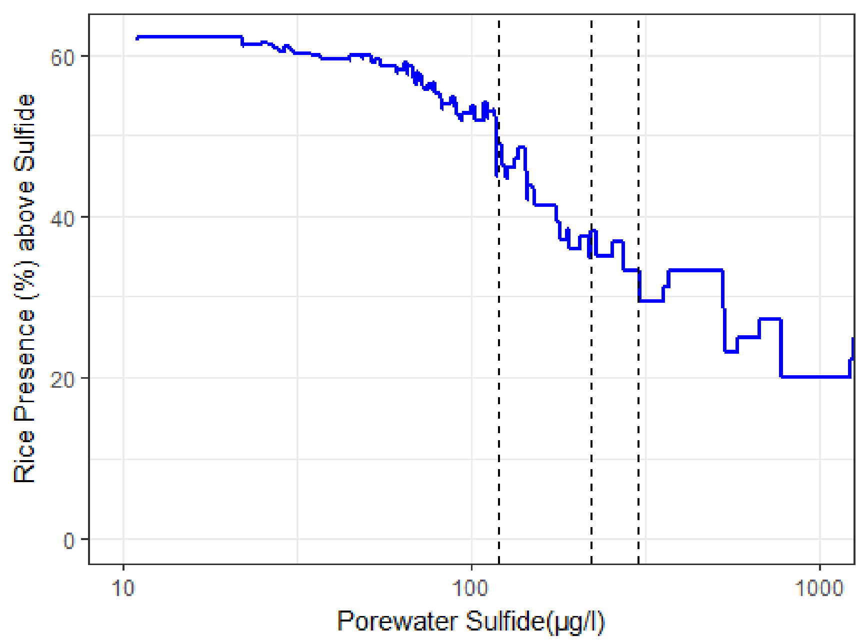
Appendix 4 of the TSD provides measurements of wild rice in 20 fixed sampling points over 12 years. These data show that there is tremendous annual variability in the density of wild rice stands. This variability calls into question MPCA's use of wild rice health metrics measured in a single year. Table A4-1 (page 112) describes annual variability of a factor of five or more in the same location. This variability complicates the interpretation of the field data.

FINDING: MPCA has not considered the impacts of the 2012 flooding on the representativeness of the field data from this year and has not addressed the importance of annual variability in interpreting wild rice health metrics.

Breakpoint Analysis

MPCA's first derivation of a sulfide threshold is based on the 'breakpoint' analysis of the field data described on page 69 of the SONAR and on pages 37 and 39 of the Final Technical Support Document (TSD; MPCA 2017). To derive this threshold MPCA visually examined a plot of porewater sulfide concentrations versus a measurement of wild rice health, specifically the presence of wild rice. MPCA identified a 'breakpoint' based on looking at a plot and identifying a drop in the presence of wild rice at 120 µg/l (SONAR 6E p 69). MPCA's plot is shown in Figure 3. This threshold is based entirely on MPCA's visual interpretation of the plot. In my professional judgement there is no visual evidence for a breakpoint at 120 µg/l and this value represents a visual artefact. The use of professional judgment, either MPCA's or my own, can easily lead to unconscious biases and has a high potential for erroneous conclusions.

Figure 3. MPCA Empirical Threshold Estimation



There are statistical methods that can be used to identify breakpoints, specifically piecewise regression (Seber and Wild, 1989). These methods avoid the biases associated with professional judgment and provide a statistical basis for decision making. When these methods are applied to the MPCA field dataset they indicate (1) if the lake with the highest sulfide is excluded (Bean)[1] the 'breakpoint' is more than twice the value identified by MPCA (2) if all water bodies are included[2] the breakpoint is more than 1000x the MPCA value and suggests no sulfide threshold in the field data. A summary of the statistically derived breakpoints in shown in Table 1. Note that the data was not log transformed prior to analysis as the unaltered data fit the statistical model without need for modifying the data.

Table 1. Sulfide Breakpoints Determined by Piecewise Regression	
Data Set	Sulfide Breakpoint (µg/l)
All, n=108	16000
Exclude Bean, n=107	233
Transparency > 30 cm, n=96	13000
Transparency > 30 cm and exclude Bean, n=95	244

My re-evaluation of the MPCA 'breakpoint' analysis is based on well-defined statistical methods that avoid the biases and uncertainties associated with relying entirely on professional judgement. Based on these statistical analyses, the statistically determined breakpoint is at a minimum more than twice the MPCA value, and, if Bean is included, it is orders of magnitude higher than the MPCA value. However, it is important to recognize that only 16% of the data (n=17) exhibited porewater sulfide concentrations above 300 µg/l, meaning that there are insufficient data to confidently derive a breakpoint if the true breakpoint is higher than 300 µg/l. More simply put, the true threshold could be substantially higher than 300 µg/l.

FINDING: MPCA has not justified the use of an analysis based entirely on professional judgement. When statistical methods are applied the MPCA's value based on professional judgement is found to be incorrect. Statistical methods indicate a breakpoint as high as 16,000 µg/l.

Change Point Analysis

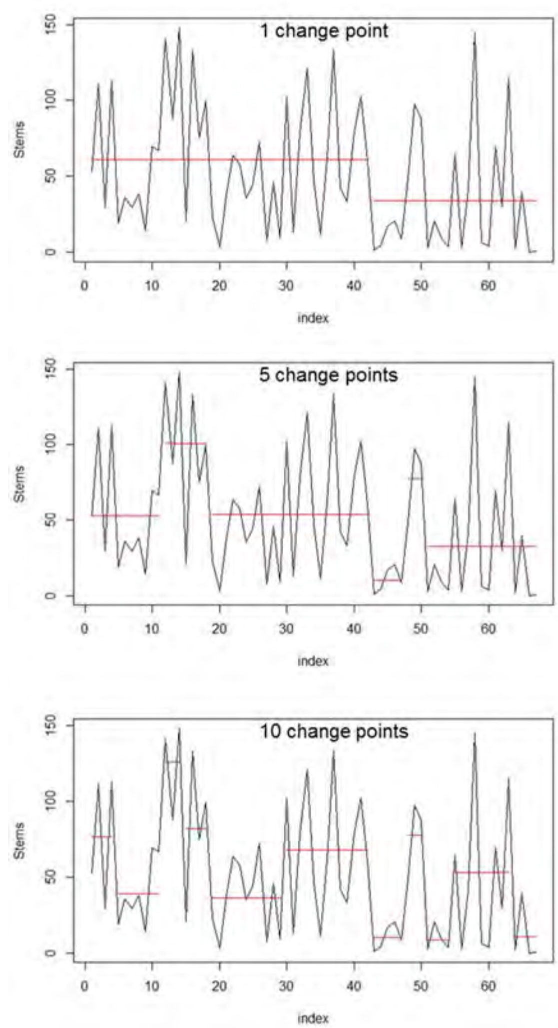
MPCA conducted another analysis of the field data using 'change point' analysis to identify a threshold (SONAR 6E p 69). This method has been described in the peer-reviewed scientific literature (Hawkins 2001, Killick et al. 2016) and does not rely on professional judgement. MPCA analyzed the wild rice stem density data using this method. In brief, the observations are ordered from lowest to highest sulfide concentration and the algorithm searches for the value above which some measure of wild rice health, in this case stem densities, are different from those below the value. The algorithm was run using only waterbodies with wild rice present (n=67). A change point of 112 µg/l was identified. There are two potential issues with this analysis: (1) the confidence limits around the 112 µg/l value are 14 to 239 µg/l, meaning that there is low precision in the estimated change point, and (2) MPCA did not

[1] MPCA refers to this as the Class B n=107 dataset

[2] MPCA refers to this as the Class B n=108 dataset

test for the presence of multiple change points, which allows the change point to be further validated (Killick et al. 2016). I reran the analysis allowing for 1, 5, and 10 change points. The change point results are shown in Figure 4. The results of these analysis show that the single change point identified by MPCA is not unique and in fact does not represent a change point that can be associated with a change in wild rice density.

Figure 4. Sulfide Change Point Analysis, Stem Density



Although MPCA limited their change point analysis to stem density, this analysis can also be applied to the presence of wild rice and to the presence of dense stands of wild rice with a stem density of greater than 40 stems per square meter (TSD page 50). This differs from the previous analysis in that it is a binary change point analysis. The algorithms from Hawkins (2001) were used for this binary change point analysis. The results are shown in Table 2. Unfortunately, this algorithm does not permit the analysis of multiple change points and is limited to the analysis of a single change point. Therefore, these values have not been fully validated and should only be used to support other lines of evidence in the analysis of sulfide thresholds. These statistical change points are all substantially higher than the MPCA threshold of 120 µg/l, supporting the conclusion that 120 µg/l is below the true threshold.

FINDING: MPCA's change point analysis fails validation and should not be relied upon. When change point analyses are performed on additional wild rice metrics they result in values substantially higher than MPCA's value, further invalidating the MPCA analysis.

Table 2. Updated Sulfide Change Point Analysis, Wild Rice Presence and Stem Density		
Data Set	Presence Breakpoint (µg/l)	Density Breakpoint (µg/l)
All, n=108	530	368
Exclude Bean, n=107	176	368
Transparency > 30 cm, n=96	274	368
Transparency > 30 cm and exclude Bean, n=95	274	368

Dose-Response Analysis

Although the methods described above are well founded in statistical theory and provide important information regarding the relationship between sulfide and wild rice health metrics, these methods are not typically used to derive protective thresholds. Typically a dose-response statistical model would be used for this sort of data, such as the relationship shown on pages 119-120 of the TSD for probability of wild rice presence versus pore water sulfide. However, the field data do not fit the requirements of such a model; specifically (1) there is no well-defined no-effect level due to high variability at all sulfide concentrations, and (2) sulfate is a nutrient required for plant growth (TSD page 53). At very low sulfate concentrations wild rice health may be reduced, a relationship that does not fit the statistical model used by MPCA. Thus, although MPCA does fit the field data to a dose-response curve, the data do not fit the assumptions of the statistical model and therefore any sulfide threshold derived using this method should not be used. Based on these challenges associated with a typical dose-response model and the fact that filed data do not fit the model, I selected binary analysis as a simple and robust method for analyzing these data for changes in wild rice health at higher sulfide concentrations.

FINDING: MPCA's dose response modeling does not meet the assumptions of the analysis, does not fit the data, and should not be used to derive an EC_{10}.

Binary Analysis

Binary analysis presents an alternative method for analyzing the relationship between wild rice and sulfide that is not affected by the issues that make the dose-response modeling of the field data invalid. Binary analysis is accomplished by combining data with similar sulfide concentrations into bins and analyzing wild rice health metrics for each bin. The bins were set by the statistical software such that the target number of samples in each bin is as close to 10 as possible. A sample size of 10 seeks to optimize the increased statistical power associated with a large sample size while maintaining sulfide ranges that are narrow enough to be useful for deriving a threshold. The resulting dataset was analyzed using two complimentary methods: (1) testing if there is any influence of sulfide on wild rice health metrics using a numeric data binning function (R function ‘cut2’; Harrell 2017) and the chi-squared test, and (2) determining which concentration bins exhibit reduced wild rice health by comparing the confidence limits for the wild rice health metric in each concentration bin using the confidence intervals for binomial probabilities (R function ‘binconf’; Harrell 2017). It is important to note that the analysis may be unable to determine which bins have reduced health metrics even if a significant difference between sulfide concentration bins is found (Zar 1984; Lyman Ott 2010)

Two wild rice health metrics were subjected to binary analysis: (1) the presence of wild rice, and (2) the presence of high density stands of wild rice (>40 stems per square meter). These same metrics were used by MPCA in their analyses (presence/absence of rice, presence/absence of high density stands of rice) (SONAR 2 page 69). My analyses are shown in Figure 5. In the top two plots of Figure 5, the data points represent the proportion of waterbodies with wild rice present for each sulfide concentration bin. The error bars represent the 95% confidence intervals. When the confidence limits for two concentration bins overlap then the difference between the percentages of locations with wild rice present in not significantly different using a typical 95% confidence level. The presence of high densities of wild rice is shown in the bottom two plots of Figure 5. These plots clearly show that there is no statistically significant difference in the wild rice health metrics for the sulfide concentrations bins. The plots do suggest some decrease at the top two concentrations bins, but the difference is minor and not statistically significant. Thus, these results indicate that the MPCA threshold of 120 µg/l is too low, and higher thresholds (2-3) are just as protective as the MPCA threshold. Furthermore, there are too few data points in the field data with porewater sulfide values high enough (300 µg/l or higher) to reliably determine a true upper threshold (Table 3).

Figure 5. Sulfide Binary Analysis, Wild Rice Presence and Stem Density

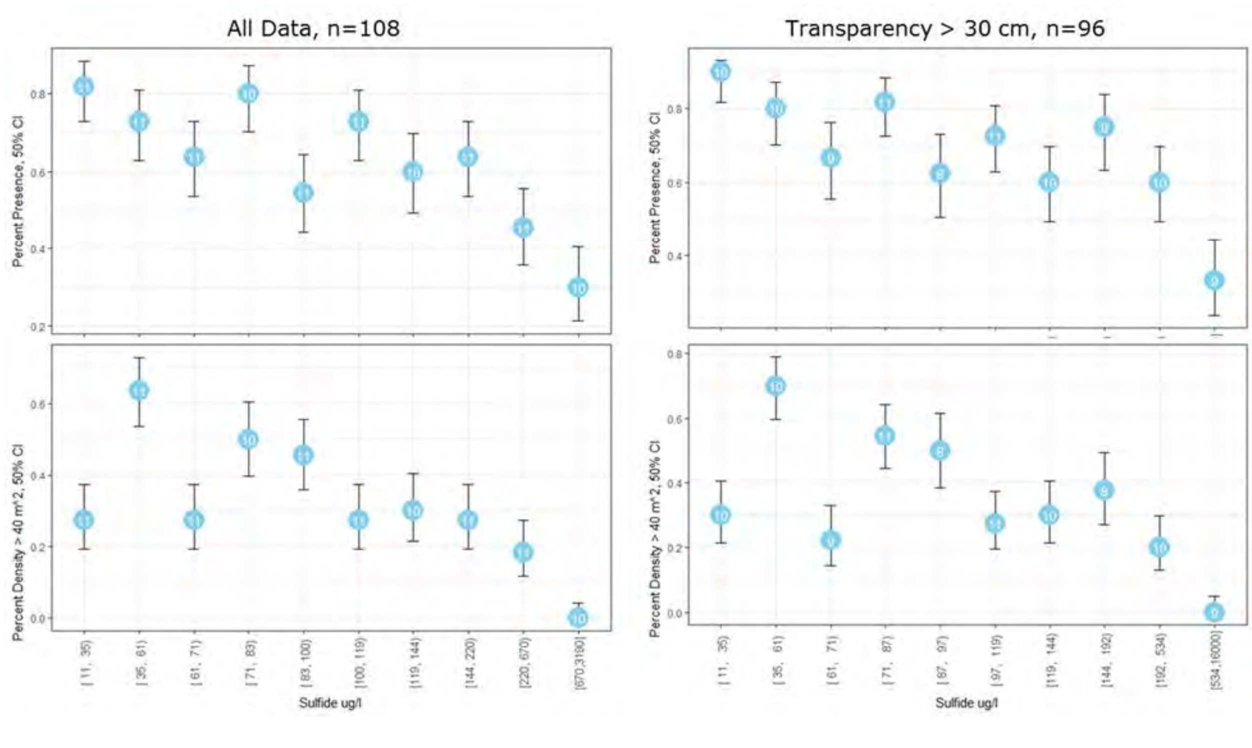


Table 3. Percentage of Sites with Sulfide >300 µg/l	
Data Set	Percent with Sulfide >300 µg/l
All, n=108	16%
Exclude Bean, n=107	15%
Transparency > 30 cm, n=96	14%
Transparency > 30 cm and exclude Bean, n=95	13%

FINDING: This analysis is more robust than the MPCA dose response analysis. The results of the binary analysis indicates that the MPCA threshold of 120 µg/L is not reasonable or valid. The MPCA value is too low and the true threshold is much higher.

Summary

When I analyzed the field data using appropriate methods I found no evidence that increasing the sulfide threshold to values 2-3 times the MPCA value would lead to a discernible decrease in the health of wild rice. There is insufficient data to reliably evaluate higher thresholds.

MPCA unreasonably excludes the alternative threshold of 300 µg/l in TSD Appendix 9. MPCA argues if you test one threshold, you cannot test another using the same data. MPCA's justification for excluding these data is unreasonable. MPCA indicates that a basic tenet of statistics is that a data point cannot be reused in a statistical analysis. While strictly speaking this is true, MPCA fails to acknowledge that the field data is being reused for a large number of statistical analyses. Typically the reanalysis of data in this manner represents exploratory data analysis. In this situation, the statistician must be very careful in ensure that they acknowledge the uncertainty in this approach. The statistician need not dismiss the analysis but rather should account for these factors by weighing each line of evidence when drawing conclusions. MPCA does offer an alternative analysis of the 300 µg/l threshold. The results indicate that 120 and 300 µg/l are similarly protective with respect to presence/absence, but density is reduced when 300 µg/l is compared to 120 µg/l.

FINDING: Based on the weight of evidence, I conclude that the 120 µg/l sulfide threshold proposed by MPCA is overly conservative and the true threshold is at least 2-3 times higher than the MPCA threshold.

SULFATE EQUATION COMMENT (RULE 7.26-8.2; SONAR 6E P75-77)

MPCA developed an equation to predict a waterbody specific sulfate standard based on sediment Total Organic Carbon (TOC) and iron and the sulfide threshold using multiple binary logistic regression (MBLR). I recalculated water body specific sulfate thresholds using the MPCA method and different sulfide thresholds to test the stability of the sulfate equation and its ability to predict wild rice health. I found a significant conflict in the performance of the equation that indicates that the equation does not provide sound predictions of the relationship between sulfide and sulfate and therefore is an unreasonable standard. Specifically, if the sulfide threshold is increased one would expect the sulfate threshold for a given water body to also increase. I found that in a large number of instances, when the sulfide threshold is increased the sulfate threshold decreases. A few examples are shown in Table

4. If elevated sulfate leads to high sulfide then we should not see these trends in sulfate thresholds. Thus, the MBLR truly is unable to predict sulfate from TOC and Fe for a porewater sulfide threshold and has limited predictive power. Any equation used to derive a sulfate standard must yield higher sulfate standards in a waterbody when higher sulfide thresholds are used. The fact that this is not true for the MBLR equation indicates that the equation is likely to lead to erroneous conclusions and is potentially a statistical anomaly. The use of such an equation presents a fundamental flaw in MPCAs approach and should not be used.

Table 4. Sulfate Standards from the MBLR Equation for Various Sulfide Thresholds

Waterbody	Sulfate Standard (mg/l) based on n=108			
	Sulfide 120	Sulfide 176	Sulfide 220	Sulfide 274
Pleasant	6.8	10.1	24.6	29.3
Second	148	806	1042	615
Lady Slipper	26.5	142.3	126.8	115.5
Duck Lake WMA	17.0	25.1	76.0	71.8
Sturgeon	69.6	596	409	300

FINDING: MPCA's equation does not fit the conceptual model of the relationship between sulfate and sulfide, TOC, and iron. The equation violates a basic rule that if the permissible sulfide threshold is increased the sulfate threshold should also increase. The equation does not accurately described the relationship between sulfate and sulfide and cannot be used for deriving sulfate thresholds.

VALIDATION AND ERROR RATES (RULE 7.26-8.2; SONAR 6E P75-77)

A critical component to any statistical model is model validation and an examination of the error rates. One component of model validation is 'does the model fit our understanding of geochemical processes?' In section D, pages 42-43 of the TSD, MPCA admits that the model used to derive the sulfate threshold are not based on the geochemical processes that relate sulfate to sulfide, TOC, and iron. In fact, the model is based solely on fitting a statistical model to the data. The reliance on a statistical model does not disqualify the MPCA equation, but in validating the model it is important to assess how well the model fits know geochemical processes, as demonstrated above in my comments on the MPCA equation, the model fails this simple test. Specifically, if TOC and iron are constant and the acceptable level of sulfide is raised, the model must derive a higher sulfate threshold. The model does not function in this way. In fact, when the entire dataset is examined for the example sulfide thresholds shown in Table 4, the highest sulfate threshold is not associated with the highest sulfide thresholds for the majority of waterbodies. Any statistical model that is inconsistent with known geochemical processes in this way should be rejected.

Even though the MPCA model fails the validation criteria given above, I also looked at error rates and how MPCA assessed the validity of the model. MPCA calculated error rates by looking at how often the equation correctly determines if the sulfide measured in porewater exceeds the sulfide threshold of 120 µg/l. MPCA also examine the error rates for a number of other thresholds (TSD page 57=58, Table 1-10). This is an incorrect way to validate the model and overestimates the accuracy of the model. If the purpose of the model is to protect the health of wild rice then a more appropriate determination of the error rate is how well the model predicts wild rice health. The following is an excerpt from the public hearing transcript from the 23 October hearing in St. Paul. Page 152, lines 14-25

MR. BOCK: Michael Bock. I think she already stated my question or clarifying. When you're talking about error rates, you're talking about the ability to predict the sulfide concentration above and below the threshold and not -- and that error ['area' in transcript'] has nothing to do with the presence or absence of wild rice if the equation predicts it's above or below the threshold based on the sulfate. Is that a correct interpretation?

MR. SWAIN: The error rates we've been discussing are how accurately the sulfide concentration is predicted and has nothing to do with wild rice presence and absence, I agree.

This is a critical observation. The standard should be validated against wild rice health metrics and NOT solely on predicted porewater sulfide. Given that wild rice health metrics are available in the dataset, there is no reason not to examine if the equation accurately predicts the health of wild rice.

The following tables show how two wild rice health metrics (presence/absence of wild rice or presence/absence of high density wild rice [> 40 stems m^2] are related to waterbodies that either (1) have porewater sulfide greater that a given threshold (120, 176, 220, and 274 µg/l) or (2) have sulfate in surface water exceeding the calculated standard based on a given sulfide threshold (120, 176, 220, and 274 µg/l). These statistics were calculated using the n=96 dataset (transparency > 30 cm), and the columns sum to 100%, but the trends are consistent with the results from the complete dataset.

Table 5. Wild Rice Health Metrics versus Exceedances of Sulfide and Sulfate Thresholds

Percentage of Sites with Wild Rice Relative to Sulfide Threshold

	120 µg/l		176 µg/l		220 µg/l		274 µg/l	
	< 120	>120	<176	>176	<220	>220	<274	>274
Wild Rice Present	24	45	25	52	28	50	27	62
Wild Rice Absent	76	55	75	48	73	50	73	38

Percentage of Sites with Wild Rice Relative to Sulfate Exceeding the Sulfide based Threshold

	120 µg/l		176 µg/l		220 µg/l		274 µg/l	
	< 120	>120	<176	>176	<220	>220	<274	>274
Wild Rice Present	27	40	30	35	29	43	29	56
Wild Rice Absent	73	60	70	65	71	57	71	44

Percentage of Site with Dense Wild Rice Relative to Sulfide Threshold

	120 µg/l		176 µg/l		220 µg/l		274 µg/l	
	< 120	>120	<176	>176	<220	>220	<274	>274
Dense Wild Rice Present	57	82	60	86	61	88	61	92
Dense Wild Rice Absent	43	18	40	14	39	13	39	8

Percentage of Site with Dense Wild Rice Relative to Sulfate Exceeding the Sulfide based Threshold

	120 µg/l		176 µg/l		220 µg/l		274 µg/l	
	< 120	>120	<176	>176	<220	>220	<274	>274
Dense Wild Rice Present	27	40	30	35	29	43	29	56
Dense Wild Rice Absent	73	60	70	65	71	57	71	44

These results show that the error rate for sulfate is much larger than the error rate for sulfide. Meaning that the equation based sulfate thresholds do a poor job of predicting wild rice health. Furthermore, the error rates for wild rice health based on sulfide and sulfate are virtually identical for the various sulfide thresholds. Based on these data I conclude that the MPCA threshold of 120 µg/l is no more predictive of wild rice health that 176, 220, and 274 µg/l, and perhaps higher thresholds. These analysis confirm the conclusion that the MPCA standard does a poor job of predicting wild rice health.

Finally the body of work produced by MPCA suffers from a fundamental statistical flaw. One should not use the same dataset used to derive a model to validate the model. A statistical model should be validated using an independent dataset, a process known as cross validation (Seymour 1993). Throughout this process MPCA has proposed various datasets for cross validation but I only address the validation dataset described in the TSD in these comments. MPCA devotes very little discussion to the validation dataset (TSD page 44 and 59) but based on a review of the raw data and the TSD I have determined that:

- The validation dataset consists of 47 water bodies
- The data was collected from the SAME waterbodies used to develop the equation and the SAME years, but the specific year used to derive the equation was not used in the validation dataset.

This clearly does not represent an independent dataset and therefore the model has not been cross validated. In order to properly validate the model MPCA must use a truly independent dataset. They must sample waterbodies NOT included in the development of the model AND the must use data from year OTHER than 2012 and 2013. Based on these deficiencies, MPCA has NOT cross validated the model used to derive the standard. A model that has not been validated is inappropriate for rule making and represents an unreasonable standard.

FINDING: MPCA has not validated the components of the rule, has not provided a true validation dataset, and has not properly evaluated error rates. Because of these deficiencies MPCA has not properly evaluated the effectiveness and reasonableness of the rule.

RECOMMENDATIONS

Based on my analysis of the sulfide threshold (Rule 7.20; SONAR part 6E) and sulfate equation (Rule 7.26-8.2; SONAR 6E p75-77), I am recommending the following changes:

1. Establishing a toxic porewater sulfide threshold of 120 µg/l is not reasonable.

2. MPCA's equation to predict a waterbody specific sulfate threshold based on TOC, iron, and the sulfide threshold is not reasonable.

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Comments on:
The proposed Amendment of the Sulfate Water Quality Standard Applicable to Wild Rice and Identification of Wild Rice Waters.
OAH Docket NO. 80-9003-34519
Revisor NO. RD4324A

November 21, 2017

Comments by: Robin L. Richards, REM on behalf of the Iron Mining Association of Minnesota

Comments addressing: Water Quality Criteria Development Process

Background
For the past 30 years, I have been providing consulting services focused on water quality protection. In this role I participated in work groups or committees tasked with commenting on or directly developing water quality criteria and their implementation into Clean Water Act programs. This participation has extended from the 1990 development of the USEPA "Technical Support Document for Water Quality-based Toxics Control" to serving on several state work groups dealing with state-specific water quality protection (e.g., the Illinois Sulfate Standard work group, 2002 to 2007). I was appointed and was an active member of the Minnesota Wild Rice Study Advisory Committee. My educational background is in biochemistry and plant physiology. I am a principal with Ramboll Environ US Corporation (Ramboll Environ) and serve as the Water Management and Planning Department Manager.

Executive Summary
MPCA did follow a few of the elements of the standard water quality criteria development process, however the elements that were either not followed or addressed and where MPCA did not incorporate the state of the art understanding/methodologies in criteria development have resulted in minimal confidence in the certainty of MPCA's proposed criterion in ultimately achieving protection of wild rice. Specific to my comments, MPCA has not demonstrated the reasonableness of the following:

- The porewater sulfide concentrations impacting wild rice health (SONAR 6.E.2)
- The MBLR sulfate equation (SONAR 6.E.4 and 6.E.5)
- The porewater sulfide analytical method (SONAR 6.E.7)

Introduction
<u>Why are water quality criteria developed?</u> *What has been left out in SONAR 4.A. pg 26 to 28?*
Water quality criteria are intended to prevent the occurrence of toxic pollutants in toxic amounts, as per Section 101(a)(3) of the Clean Water Act, and protect designated / beneficial uses of water (e.g., aquatic life, human health).

- Aquatic life criteria are intended to assure that toxic pollutants are not present in concentrations that would cause acute and or chronic adverse impacts on aquatic life.
- Human health criteria are intended to assure that toxic pollutants are not present in concentrations that would cause adverse impact to persons who eat fish or shellfish and/or drink the water. Similarly, wild rice criteria would be intended to assure that toxic pollutants not be present in concentrations that would cause acute or adverse impacts to wild rice.

In understanding the intention of water quality criteria, clear definitions of "toxic amount" and of "adverse impact" are needed. Hence, EPA, as per the Clean Water Act, develops water quality criteria using processes that result (with defined confidence), what dose of a chemical causes what type of response(s) to an organism[1]. Put simply, a dose-response curve is developed where the response or "adverse impact" is concrete and reproducible.

Furthermore, when the standard water quality criteria development process is followed resulting in a reliable dose response curve, there is an anticipation that a waterbody, all other physical and biological factors being equal, will have improvement in aquatic life and community health as the aquatic life criteria for toxic pollutants are achieved.

By the 1990's, EPA and the states were fully engaged in the control of the discharge of toxic pollutants in toxic amounts through the adoption of water quality criteria and implementation procedures. As anticipated, there are numerous examples where the levels of toxic pollutants were reduced in a water body, and related adverse impacts to aquatic life were no longer observed.

MPCA has not clearly defined the dose-response or toxic amount and the resulting specific adverse impact. These are the necessary underpinnings for a water quality criterion being confidentially developed and implemented to assure protection of the designated use.

Protective Level of Porewater Sulfide

MPCA discusses their process used to develop the protective level of sulfide (SONAR 6.E.2, TSD pg 31 – 39, 113-120) where MPCA attempted to develop dose-response curves between sulfide and a variety of "effects". However, there are errors in MPCA's development and presentation of their version of "dose-response" curves as discussed below.

<u>Pastor et al. 2017</u>

Pastor, et.al published their wild rice hydroponics sulfide toxicity testing data in Ecological Applications 27(1), 2017, "Effects of sulfate and sulfide on the life cycle of *Zizania palustris* in hydroponic and mesocosm experiments". An EC50 of 245 µg/L was statistically determined and presented in the paper[2]. Very few details were provided in the published paper on the data used, definition of EC0, EC10, or definition of initial conditions. The peer-reviewed article does not contain an EC10 so it should be noted that any EC10 based on these data were not evaluated during the peer-review process for publication. In a meta-analysis performed for MPCA, Pastor calculated an EC10 of 299 µg/L.

MPCA conducted additional meta-analysis of the Pastor data to derive an EC10 using MBLR. MPCA did respond to questions on the data and statistical analyses, which were used to define various EC10s as presented in Attachment 1. However, as noted by the Minnesota Chamber of

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[1] USEPA. 1991. Technical Support Document for Water Quality-based Toxics Control. Available on-line: https://www3.epa.gov/npdes/pubs/owm0264.pdf
and
Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 1985. Guidelines for Deriving Numeric National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. EPA 822/R-85-100 or PB85-227049.National Technical Information Service, Springfield, VA.
and
USEPA. 1994 and subsequent online updates. Water Quality Standards Handbook. EPA-823-B-94-005a&b. Washington, DC: U.S. Environmental Protection Agency, Office of Water. Available online at: https://www.epa.gov/wqs-tech/water-quality-standards-handbook

[2] EC0, EC10, EC50 = Effect Concentration impacting 0% of (test) organisms, or 10% of organisms, or 50% of organisms.

Commerce[3] subsequent to Pastor's presentation of sulfide hydroponic work plans to the MPCA, interim results, and final results, the quality of the test design and execution are not considered of the quality typically used for determine chemical toxicity as per Good Laboratory Practices[4]. This is reflected by a variety of things:

- The scatter (huge variability) of the weight change
- The gap in sulfide concentrations between 100 µg/L and 1000 µg/L
- The high variability in the measured sulfide concentrations the implicit lack of control of aqueous sulfide
- The lack of daily sulfide measurements
- Treatment of what is really 3 range-finding tests as definitive tests.

Related to statistical analyses, some of the key decisions by MPCA used to calculate EC10s included the following:

- Considering normalizing the negative weight changes by assigning a negative growth as a zero value (identified as "growth" in Attachment 1 figures)
- Calculating the weight change by difference with the initials where the initials are an average of a random subset of the initial set of seedlings
- Defining the EC0 as control * 0.9 by inputting the MDL concentration for sulfide into the MBLR equation and using the equation output as control/EC0.

While the normalization certainly changes the shape of the sigmoidal curve and visually reduces the huge variability in growth or weight change, but it does not communicate the fact that the scatter in that data exists. It is not possible to generate the initial set of conditions (weights) as MPCA used a random subset. It is not clear whether MPCA has generated a different random subset and conducted a sensitivity analyses to determine that this is valid approach; nor is there an evident rationale for not using the entire initial weights. As presented in Attachment 1, an option of using the geomean of the minimally generated sulfide measurements was investigated by Ramboll Environ. It is not appropriate to use a geomean on this type of data, a time-weighted average is more applicable.

As presented in Attachment 1, when the influence of the sulfide test measurement issues are considered, the sulfide EC10s for the Pastor data vary by more than a factor of two, ranging from 103 µg/L to 255 µg/L. Given the variability in these EC10s and significant criticisms of the Peer Review Panel (see Section 3.2.2) these the sulfide EC10s, and any other ECs that may be based on the Pastor dataset, should be considered rough estimates and weighted less heavily in the determination of a porewater sulfide protective value then the other lines of evidence.

<u>Field Data</u>

My colleague, Dr. Michael Bock, has submitted in-depth comments on the MPCA errors in identifying the porewater sulfide threshold concentration. To reiterate, the MPCA presentation of probability of wild rice presence versus porewater sulfide is flawed as there is not a well-

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[3] MCC. 2015. Technical Analysis of MPCA March 2015 Proposed Approach for Minnesota's Sulfate Standard to Protect Wild Rice.

[4] EPA Good Laboratory Practices (GLP) available on-line: https://www.epa.gov/compliance/good-laboratory-practices-standard-operating-procedures

And

OECD Good Laboratory Practices available on-line:

http://www.oecd.org/chemicalsafety/testing/goodlaboratorypracticeglp.htm defined no-effect level due to the high variability in porewater sulfide concentrations and the fact that sulfate is a necessary wild rice nutrient (TSD pg 53).

Summary

The proven and known approach of developing water quality criteria by developing a dose-response curve has not been reasonably demonstrated by MPCA. Their presentation contains errors and these errors undermine the confidence in understanding and defining the relationship between porewater sulfide and wild rice health.

State of the Art Science

State of the Art Examples of Water Quality Criteria: Direct Effect

USEPA has issued and continues to update guidance on criteria development including the type of data and statistical methods to define the dose-response. The current state of the science is recognition that the direct cause of an aquatic life (or human health) adverse impact (or effect) may not be due to water-column exposure[5]. This is similar to MPCA's finding that water column sulfate has no direct effect on wild rice.

Examples of EPA's state of the science for dose-response for water quality criteria include:

- Methylmercury where: If methylmercury in fish tissue > threshold value, chronic human health is adversely impacted (dose-response data from lab, some field, and model). And the EPA certainty in that statement and the threshold value is at a high confidence level; that is, minimal Type 1 or Type 2 errors.
- Selenium where: If selenium in the fish tissue > threshold value, aquatic life chronic health is adversely impacted (dose-response data from lab, some field, and model). And the EPA certainty in that statement and the threshold value is at a high confidence level; that is, minimal Type 1 or Type 2 errors.

The dose-response was demonstrated for fish tissue methylmercury and fish tissue selenium allowing EPA to confidentially define the "toxic amount" that caused risk to humans or impact on fish growth and reproduction. The development of water quality criteria for methylmercury, took 10 years of work (science and review) and for selenium, 19 years. Understanding of cause and effect takes time to allow thoughtful consideration given the importance of protecting humans and fish.

In addition, EPA's current state of the science, recognizes that laboratory techniques and methods, statistical computing, and ecological risk modeling have improved since the early 1990's; in effect, EPA is aware that one cannot "freeze" water quality criteria to the period of time it was first finalized. An example of this is the ammonia water quality criteria.

For example, ammonia-N aquatic life criteria, based on laboratory dose-response curves for a number of organisms, was established 1985. However, as knowledge increased about its behaviour in water and the sensitivity of invertebrate species, and as more data were validated,

[5] USEPA. 2001. Water Quality Criterion for the Protection of Human Health: Methylmercury. EPA-832-R-01-001. Available on-line: https://nepis.epa.gov/Exe/ZyPDF.cgi/20003UU4.PDF?Dockey=20003UU4.PDF
and
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revisions were issued in 2002 and again issued in 2013[6]. Now, if ammonia-N in water column is less than the determined threshold value, snail and mussel growth and reproduction will be protected (based on laboratory data). And the certainty in that statement is more than 95% confident. Besides laboratory data that demonstrate the impact of ammonia on mussel survival, there are in the field case examples where, all other factors being equal, reduction in water ammonia resulted in healthier mussel communities[7]. That is, there was documented data that a mussel community prior to ammonia reduction and post ammonia reduction showed improvement.

Defining the toxic amount of ammonia that would cause adverse impacts marched forward as science evolved. In addition to expanded knowledge, EPA removed older data that upon further review did not meet the current requirements for data validity. Clear understanding of the dose-response, the direct cause and effect, allowed science to continue support a valid and applicable criterion.

MPCA correctly states that water column sulfate does not have a direct effect on wild rice – there is no dose-response curve for sulfate vs. wild rice survival, growth, or reproduction. MPCA presents sulfate as having an indirect effect of wild rice. MPCA has defined porewater sulfide as a toxicant causing adverse impact to wild rice. However, as discussed previously, there is minimal confidence in the sulfide threshold developed by MPCA and MPCA's presentation of dose-response relationship is flawed.

Using state-of-the-art methods, EPA has shown more than once that a non-water column criteria can be developed from dose-response (aforementioned fish tissue based criteria) and that the confidence one typically has with laboratory water column data, can be achieved in defining a "toxic amount" in fish tissue. Without confidence in the dose-response for porewater sulfide, a "toxic amount" is difficult to define for use in assuring that protection of designated use is achieved. If MPCA followed the longstanding EPA approach to water quality criteria development, the wild rice water quality standard would be based on the chemical causing the direct effect, porewater sulfide.

State of the Art: Water Column Translation of Direct Effect

MPCA has created a challenge to translate the direct cause (porewater sulfide) of a wild rice effect to water column sulfate concentration. The water column concentration is used in water regulatory programs to assure toxic amounts are not discharged or that designated uses are attained (and maintained) based on a standard. EPA has not attempted to establish water quality criteria based on an indirect cause of the effect. EPA's water quality criteria are based on the direct cause. As discussed earlier, EPA has recommended criteria that are not water-column based i.e., selenium fish tissue, methylmercury fish tissue.

However, the implementation of these criteria to water column levels, or translation to a water column concentration, is considered a separate activity and is not part of the EPA's national recommended criteria. What this means is that while EPA criteria are suitable (and typically

[6] USEPA. 2013. Aquatic Life Ambient Water Quality criteria for Ammonia – Freshwater. Available on-line: https://www.epa.gov/sites/production/files/2015-08/documents/aquatic-life-ambient-water-quality-criteria-for-ammonia-freshwater-2013.pdf

[7] U.S. Fish and Wildlife Service (USFWS) Midwest Region Freshwater Mussel Threats Geospatial Database.
DL Strayer. 2008. Freshwater Mussel Ecology: A Multifactor Approach to Distribution and Abundance.
J Farris and J VanHassel. 2007. Freshwater Bivalve Ecotoxicology.

encouraged) to be adopted into state water quality standards programs, translation of criterion to water column concentration is not encouraged by EPA to be part of state regulatory water quality standards. It is recognized that the models developed by EPA to go from fish tissue level to water column level are very site-specific and typically data intensive (e.g., multiple years of data needed).

The EPA does develop implementation guidance and solicits public comment on the guidance. The implementation guidance for methylmercury (to generate a total mercury water column concentration for a water body) was issued 9 years after the final fish tissue methylmercury criterion was issued[8]. EPA has not yet finalized the implementation (and monitoring) guidance for selenium fish-tissue; work that began in 2004[9]. Point being: the amount of data and information needed takes time to generate, validate, and utilize to be able to develop the sound models and recommendations to translate the direct effect (methylmercury in fish tissue or selenium in fish tissue) to water column concentrations (mercury in water column or selenium in water column). Implementation of criteria has enforcement implications for both a state agency and a discharger. It is difficult to develop the confidence in a model as one would expect for incorporation into regulation, one size does not fit all for implementation or translation of fish-tissue criteria to water column concentrations. As presented by MPCA, the MBLR sulfate equation (which is a model) is not aligning with porewater sulfide or wild rice health (MPCA uses the term “misclassification”) for an alarming number of waterbodies (TSD, pg 48 to 62, 67 to 83; SONAR pg 77 to 79) as one considers the regulatory impact on agency decisions and actions.

MPCA should take a page from EPA and use guidance to implement the porewater sulfide threshold. Certainly MPCA would have far more flexibility to allow implementation of the porewater sulfide threshold concentration into water column sulfate concentrations to exist as guidance, and not regulation. This would also allow MPCA the nimbleness needed to respond to additional data, evolving understanding the geochemistry of wild rice waters, and improved statistical methods.

Others will be commenting on the errors underlying the development of the MBLR sulfate equation including the selection of field results, the differences in the MPCA databases used to develop and validate the equation including how MPCA elected to use various databases, the high misclassification rate for the results of the MBLR equation, and MPCA’s dismissal of alternative statistical methods to evaluate the relationships between sulfide, sulfate and wild rice.

MPCA added in from the draft TSD to the final TSD reference to the state of Vermont phosphorus standard rulemaking process (TSD pg 55, 62-63, SONAR, pg 77 -78) as a comparison of false negatives and false positives or misclassification rate as found for the MBLR sulfate equation to the Vermont process.

However, MPCA neglected to explain the Vermont process and highlight how the process was very different from the MPCA approach for the MBLR sulfate equation. In particular, specific to the implementation of the Vermont nutrient criteria, an integrated approach to implementation is

[8] EPA. 2010. Guidance for Implementing the January 2001 Methylmercury Water Quality Criteria. Available on-line: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1007BKQ.PDF?Dockey=P1007BKQ.PDF
[9] EPA. 2016. Technical Support for Adopting and Implementing EPA’s 2016 Selenium Criterion in Water Quality Standards, Draft. Available on-line: https://www.epa.gov/sites/production/files/2016-10/documents/technical-support-adoption-implementation-selenium.pdf

also presented by Vermont[10]. The integrated approach used by Vermont allows for compliance with nutrient criteria to be evaluated by either comparison to nutrient criteria or by comparison to nutrient response variables (e.g., macroinvertebrate community health). This integrated approach is used <u>because of</u> the misclassification rates of 20 to 40%.

MPCA is not proposing an integrated approach to assessing compliance with the MBLR sulfate equation. Compliance is only evaluated based on comparing the equation water column sulfate and the monitoring results for sulfate. An integrated approach that might be considered is the presence and health of the wild rice in the wild rice water body and if the wild rice were present and healthy, then compliance is demonstrated. Given the amount of MPCA MBLR sulfate misclassification rate, an integrated approach is warranted.

Summary

The evolution to developing water quality criteria continues to focus on the direct effect and the dose-response, whether the direct effect impacting designated use of water body is found in the water column or not. EPA has water quality criteria that are based on fish-tissue and continue to be based on dose-response. MPCA's identification of porewater sulfide as the direct cause of an adverse impact on wild rice is similar to EPA's fish-tissue based criteria. However, EPA has taken the time to generate robust and valid data and methods to translate the fish-tissue criteria to water column chemical concentrations and the translation is adopted as guidance; not a water quality criterion or rule. MPCA, by adopting into rule the translation of the porewater sulfide to water column sulfate with the development of the MBLR sulfate equation, needs a level of confidence (e.g., far lower level of misclassifications) that is not currently shown. In addition, Vermont, in recognition of their high misclassification rate (similar to MPCA's misclassification rate) for nutrients, is using an integrated approach for implementation while MPCA is not.

Porewater Sulfide Analytical Method (SONAR E.7)

MPCA correctly notes that to use the MBLR sulfate equation, sediment porewater must be sampled and analyzed for sulfide. MPCA states that for new or expanding dischargers, the discharger must collect and analyze the samples as per the MPCA's "Sampling and Analytical Methods for Wild Rice", July 2017. On page 12 of this document, MPCA states that the analytical method for porewater sulfide is Standard Methods 4500-$S2^-$ E. Gas Dialysis, Automated Methylene Blue Method. Standard Methods presents limited data on precision and bias of the method (one single laboratory, spiked laboratory water at 4 concentrations for precision and two samples for bias). Standard Methods does not identify the method detection limit (MDL) nor the reporting limit (RL) expected for method 4500-$S2^-$ E Sulfide.

MPCA does list acceptable analytical performance but neglects to identify the required MDL. My opinion is given MPCA's use of a porewater sulfide threshold of 120 ug/L, the MDL should be at least 3 to 5 ug/L and the RL 10 to 15 ug/L to have confidence in using the data to derive an enforceable sulfate standard. The accuracy (bias) statement presented by MPCA is different than that included in Standard Methods. Further, no documentation or data on the development of an acceptable recovery of 80 to 100% (versus 97.6% to 104.2%) is provided by MPCA. The typical commercial lab quality assurance and quality control packages were not presented to the

[10] Vermont DEC. 2014 rev 2016. Nutrient Criteria for Vermont's Inland Lakes and Wadeable Streams: Technical Support Document. Available on-line: http://dec.vermont.gov/sites/dec/files/wsm/Laws-Regulations-Rules/2016_12_22-Nutrient_criteria_technical_support_document.pdf

Wild Rice Advisory Work Group in support of the Minnesota State health laboratory (state laboratory) that generated the porewater sulfide analytical results. Therefore, it is not known how they developed their MDL or RL, how they developed their calibration curve, what their quality control charts looked like, nor their overall precision and bias. Given the volume of analyses conducted, the details and quality control data would be most informative in having confidence in the selected analytical method and in the quality of data generated from the method. Finally, as this is not a routine method for dischargers, it would have been beneficial for MPCA to have split samples to understand interlaboratory variability (as of now MPCA, if they have any laboratory control data, only have data on intralaboratoy variability).

Finally, Ramboll has reached out to over 10 reputable certified (e.g., NELAC) commercial water testing laboratories and none of them either are set-up to run this method or routinely run this method to be confident in the quality of their results at a RL of 10 to 15 ug/L sulfide[11]. One commercial lab who has been a leader in AVS and sulfide analytical method development, Alpha Analytical, noted that colorimetric methods have a high potential for false positives due to naturally colored water. It is concerning that dischargers have limited knowledge on the accuracy and precision of the state laboratory execution of Method 4500-$S2^-$ E Sulfide and has no information on what to expect for interlaboratory variability. As I quoted Dr. Robert Hare[12] as part of my public comments during the Peer Review process[13]: "The key is measurement. Science cannot progress without reliable and accurate measurement of what it is they're trying to study. Simple as that."

<u>Summary</u>
MPCA needs to fully share all the laboratory quality control data and MDL studies conducted by the state lab to assure that MPCA, existing, new or expanding dischargers, and stakeholders are informed on the reliability and accuracy of Method 4500-$S2^-$ E Sulfide. As of now, neither MPCA nor other parties, can document the reliability and accuracy of a porewater sulfide result that will be key to deriving the enforceable sulfate standard.

In addition, as of today, no certified commercial water testing labs are available to conduct this method to a RL of 10 to 15 ug/L sulfide. As MPCA seems to have the most experience with this analytical method, they should engage in public outreach to share their knowledge with commercial labs on reliably and accurately conducting Method 4500-$S2^-$ E Sulfide.

[11] Ramboll personal phone and email communications in August 2017.
[12] Dr. Hare is a researcher in the field of criminal psychology.
[13] ERG. 2014. Summary report of the Meeting to Peer Review MPCA's Draft Analysis of the Wild Rice Sulfate Standard Study. Pg E-17

Document type
Report

Date
April 7, 2017

By
Michael Bock, PhD
Robin L. Richards, REM

ATTACHMENT **1** - EC10 SULFIDE WILD RICE (HYDROPONICS) BY MBLR

RAMBOLL ENVIRON

Calculation of EC10 using Pastor Hydroponics data, Growth

The purpose of this analysis is to confirm the source and calculation methods associated with the EC10 presented both in the Pastor published paper and by MPCA based on the Pastor data. As per MPCA, a binary logistic regression (BLR) was fitted to the Pastor hydroponics data (growth versus sulfide).

The binary logistic model is used to estimate the probability of a binary response, in this case the probability of emergence, based on one or more predictor variables, in this case sulfide. It allows one to say that the presence of a risk factor (elevated sulfide) decreases the probability of emergence. Binary logistic regression is one of the most commonly applied statistical models. However, other binary models exist that for some data sets can provide a better fit for dose response modeling (for example 5 parameter log logistic regression). For binary logistic regression, one must make sure that there is sufficient data to fit the curve and the statistician must also verify the strength of the fit.

Our analyses were conducted using R.

Summary of Pastor Data

test	uM	Reps	TWA_SO4	TWGM_SO4	Weight_Change	Growth
definitive1	12.5	3	159.21817	78.32118	2.7809524	2.7809524
definitive1	25	3	579.20467	568.29462	-0.8460317	0.0904762
definitive1	50	3	1277.28133	1255.79182	-1.8047619	0.0000000
definitive1	6.25	3	75.20567	39.17295	3.2333333	3.2333333
definitive1	Control	3	11.05000	11.05000	4.5142857	4.5142857
definitive2	10	3	159.21600	70.76421	2.3666667	2.3666667
definitive2	20	3	509.98967	496.88179	-0.4047619	0.0000000
definitive2	40	3	1009.86167	991.23102	-0.3476190	0.0047619
definitive2	5	3	82.40233	41.20921	3.1619048	3.1619048
definitive2	Control	3	11.05000	11.05000	2.2523810	2.2523810
rangefinder	10	3	181.82417	87.49147	3.3666667	3.3666667
rangefinder	3	3	59.92333	34.57361	4.2000000	4.2000000
rangefinder	30	3	825.33067	787.34099	0.3071429	0.4023810
rangefinder	90	3	2633.64133	2529.31107	-0.6293651	0.0000000
rangefinder	Control	3	11.05000	11.05000	5.1063492	5.1063492

We calculated the EC10 using the resultant equation. The EC0, the baseline response associated with 10.5 sulfide, was used to define the EC10 and EC50 as per MPCA approach.

The equation is given as:

$$c + \frac{d - c}{1 + exp(b(log(sulfide) - log(e)))}$$

Initial Sulfide as Dependent variable

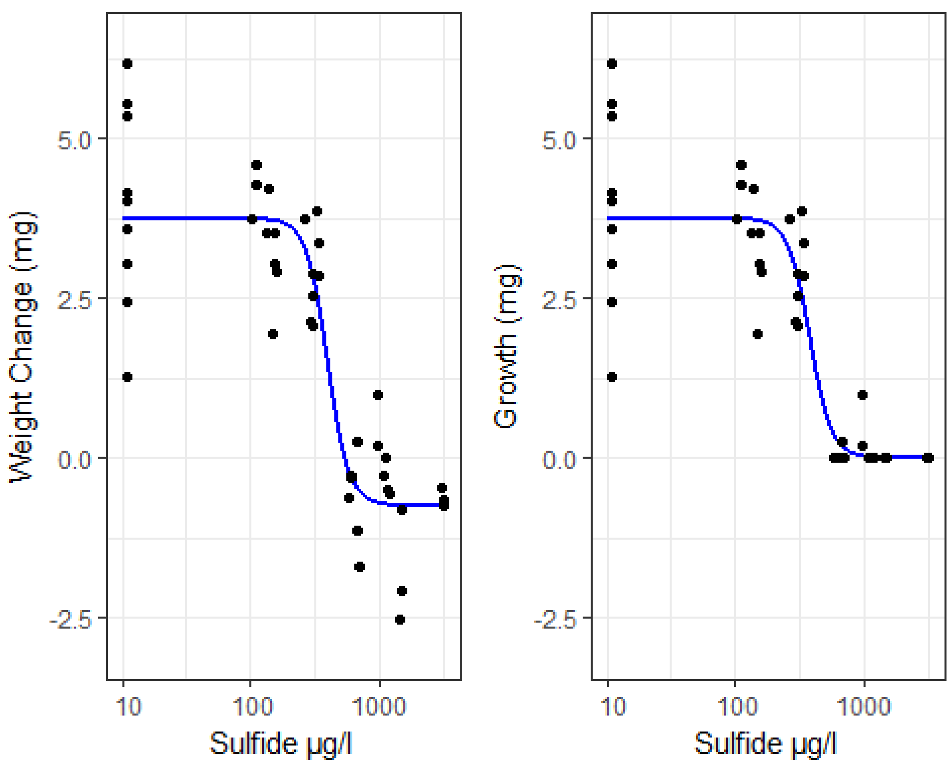
```
## [1] "Weight change based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = weight_change_mg ~ meaninitialsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
```

```
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##        5.2250        -0.7467         3.7427       403.0444

## [1] "Growth based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = growth_mg ~ meaninitialsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##      5.124624      -0.000693       3.748352     384.475375
```

Summary with Initial Average Sulfide

EC	Weight	Estimate	Growth	Estimate.1
Control	3.742656	11.0500	3.748353	11.0500
EC10	3.368390	254.7301	3.373517	250.4055
EC20	2.994124	296.2232	2.998682	293.3359
EC50	1.871328	377.9573	1.874176	384.4476

Results



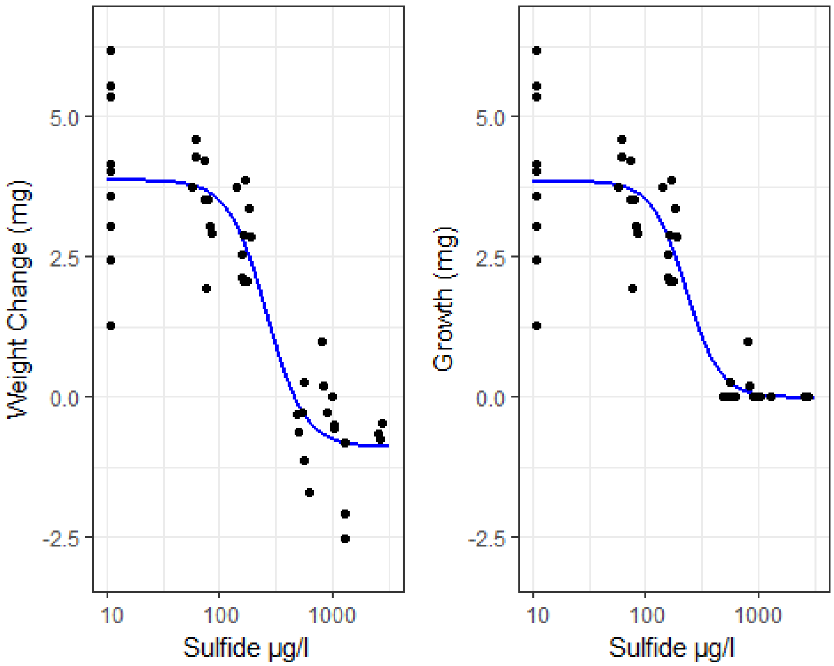
TWA Sulfide as Dependent variable

```
## [1] "Weight change based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = weight_change_mg ~ arithmeticTWMsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##        2.5874        -0.8957         3.8624       262.8643

## [1] "Growth based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = growth_mg ~ arithmeticTWMsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##       2.88824       -0.01358        3.84122      230.26192
```

Summary with TW Average Sulfide

EC	Weight	Estimate	Growth	Estimate.1
Control	3.861084	11.0500	3.840622	11.0500
EC10	3.474976	103.0407	3.456560	107.5173
EC20	3.088867	139.5059	3.072498	142.3063
EC50	1.930542	226.9197	1.920311	229.7257

Results

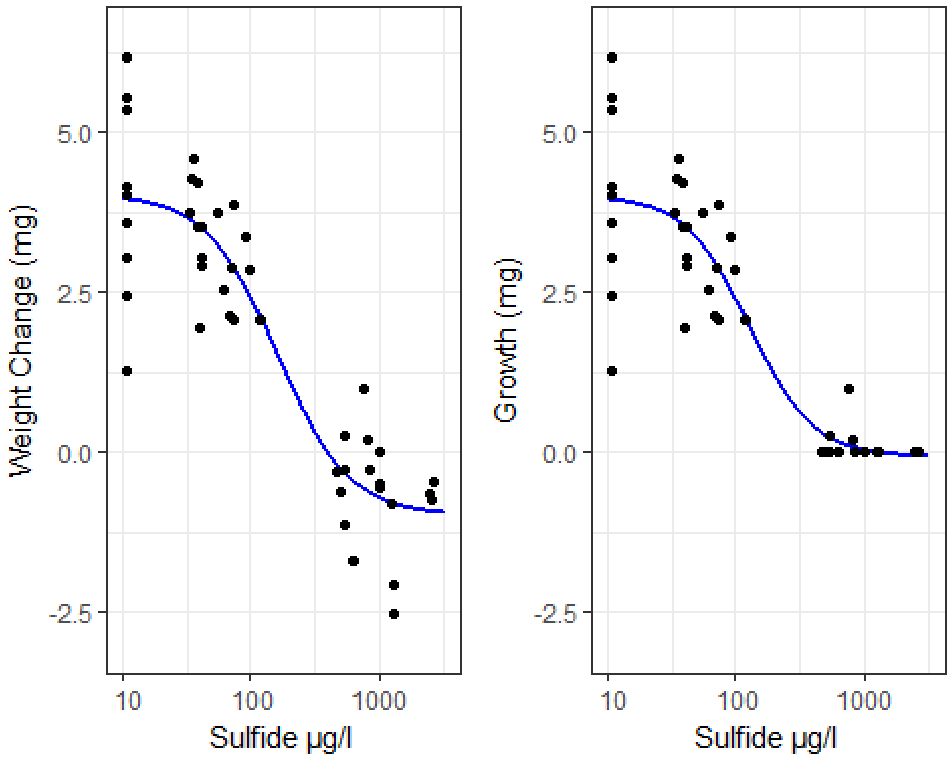


TW Geometric Mean Sulfide as Dependent variable

```
## [1] "Weight change based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = weight_change_mg ~ geometricTWMsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##         1.561         -1.001          4.028        162.497

## [1] "Growth based model"

##
## A 'drc' model.
##
## Call:
## drm(formula = growth_mg ~ geometricTWMsulfide_ugL, data = FData,     fct = LL.4())
##
## Coefficients:
## b:(Intercept)  c:(Intercept)  d:(Intercept)  e:(Intercept)
##       1.75964       -0.07114        3.99975      128.05931
```

Summary with TW Average Sulfide				
EC	Weight	Estimate	Growth	Estimate.1
Control	3.953667	11.05000	3.945855	11.05000
EC10	3.558301	37.89945	3.551269	39.06802
EC20	3.162934	59.39123	3.156684	59.71269
EC50	1.976834	127.98906	1.972927	127.44441

Results



IRON MINING ASSOCIATION OF MINNESOTA

Nov. 22, 2017

Honorable Judge Laura Sue Schlatter
Office of Administrative Hearings
P.O. Box 64620
St. Paul, MN 55164-0620

Re: OAH Docket No. 80-9003-34519

Dear Judge Schlatter:

The attached exhibits corroborate the oral testimony of President Kelsey Johnson of the Iron Mining Association of Minnesota. Her testimony was given on 10/24/2017 at the Mesabi Range Technical College.

Exhibit 1 – Oral testimony given

In addition the IMA objects to the lack of supporting evidence pertaining to rule 7053.0406. The inclusion of the EPA's Interim Economic Guidance for Water Quality Standards guides the MPCA to complete a cost analysis of their proposed changes, but that documentation has not been provided.

The Interim Economic Guidance document provided by the EPA directs: "*If the entity is privately-owned (e.g. a manufacturing facility), the analysis should consider factors such as the entity's ability to secure financing and the degree to which it will be able to pass the cost of pollution control on to its customers in the form of higher prices… the applicant must also demonstrate that compliance would create widespread socioeconomic impacts on the affected community… the applicant will need to estimate the change in socioeconomic conditions that would occur as a result of compliance. Of particular importance are changes in factors such as median household income, unemployment, and overall net debt as a percent of full market value of taxable property. For private-sector entities, the assessment of widespread impacts should consider many of the same socioeconomic conditions. The analysis should also consider the effect of decreased tax revenues if the private-sector entity were to go out of business, income losses to the community if workers lose their jobs, and indirect effects on other businesses.*"

Exhibit 2 is the Labovitz School of Business and Economics report, "The Economic Impact of Ferrous and Non-Ferrous Mining on the State of Minnesota and the Arrowhead Region." **Exhibit 3** is the United States Department of Homeland Security (DHS) Executive Summary, "The Perils of Efficiency: An Analysis Of An Unexpected Closure of the Poe Lock and Its Impact." These combined analyses highlight the economic impact of the iron mining industry not only in Minnesota but nationwide. According to the DHS analysis, the iron mining industry and affiliated industries supports 10.9 million employees and 16% of the nation's GDP. Minnesota is home to all but one of the operating iron mines in the nation and produce more than 85% of the nation's iron. That iron is used to create the steel that makes many of our everyday products.

324 West Superior Street Suite 502 Duluth, Minnesota 55802 www.taconite.org Phone (218) 722-7724 Fax (218) 720-6707

Between 2015 and 2016, four of our region's iron mines idled their facilities due to unfair pricing by international competitors. This provided the state and region with a unique perspective on what the consequences of losing the industry may be. In that time, unemployment in the region doubled, tax revenues and royalties paid by the industry fell. **Exhibit 4** is the Minnesota Department of Revenue Mining Tax Guide. The 2017 guide factors in the idled facilities during the 2015 and 2016 production years. While this was not the full effect of all mines idling, it did provide unique insight into the pricing perils facing a commodity based global industry**.** As I described in my testimony, the industry has not fully recovered from the downturn in pricing in 2015 and 2016, and many facilities are continuing to operate with diminished employee numbers and have cut costs significantly.

This proposed rule from the MPCA could not have come at a worse time for the industry as it is in the midst of a rate case with Minnesota Public Utility Commission and facing increased pressure from global competitors. The rate case will likely result in higher energy rates for the industry. Coupled with the present rulemaking, the industry is facing increased costs with limited margins. The potential of another billion dollars in investment for a concern that has not been sufficiently supported by science is too much. The IMA respectfully urges the administrative law judge to stop the rulemaking procedures until adequate understanding of the costs of compliance is sufficiently documented and justified.

Very Truly Yours,

Kelsey A. L. Johnson
President
Iron Mining Association

Kelsey Johnson Wild Rice Sulfate Testimony

Oct. 24, 2017 – Virginia, MN

Thank you for this opportunity to share the important perspective of the Iron Mining Association and our members with you today. The Iron Mining Association represents 6 taconite facilities that span the iron range and directly employ 4500 miners. Our 175 vendor members are located throughout Minnesota and North America and combined provide jobs to 11,500 people. Minnesota's iron mines contribute over 85% of the nation's domestic iron production. There is only one other state in the nation where iron mining occurs – Michigan.

The mining industry's economic impact reaches farther than Minnesota; it also plays a key role in the nation's economic health and vitality. According to a recent U.S. Homeland Security, study our industry combined with the end product made from iron – steel - supports 10.9 million jobs nationwide and supports nearly 16% of the GDP.

This isn't a new industry. We've been mining in Minnesota for 130 years, so we have the knowledge and experience to safely extract iron from the earth, while protecting nearby natural resources.

The MPCA has worked alongside the mining industry over the past 40 years to ensure that we remain a vibrant and effective industry. However, the latest rule proposed by the MPCA relies on flawed science. I'm not a scientist, but I've taken the time to learn from technical experts and read enough studies to know that a peer-review is standard for quality research. In this case, the MPCA chose not to adopt the recommendations that were identified during the peer review and instead moved ahead with this rulemaking process. Furthermore, the rule that is proposed before us today has an astounding 15-20% error rate. That means the standard predicts the wrong outcome up to one in five times. When you consider the extremely high costs to comply with this rule, there is simply no room for error.

Disappointingly, the MPCA chose not to do a cost analysis of the financial impact of the proposed rule before stepping into the rulemaking process. The early estimates given by the industry and by the communities are in the billion dollar range. The only available option for water treatment for our facilities and discharge locations is the installation of a costly reverse osmosis system. Reverse osmosis strips all nutrients and organisms out of the water, including the nutrients needed for plants to grow and fish to remain healthy. The result is that many of these facilities would be sending water downstream that is too clean.

After decades of research on this important state grain, our industry does not have confidence that the MPCA is adopting a rule that will actually have the intended results. In fact, the MPCA has said they don't know if the proposed rule would result in more abundant rice.

These are very troubling revelations that deserve thoughtful consideration before you make a decision about this rule. There is a lot at stake for this industry which provides good-paying jobs in these communities, tax revenue for Minnesota, royalties for the state's educational system and iron ore for the United States.

November 2012

The Economic Impact of Ferrous and Non-Ferrous Mining

on the State of Minnesota and the Arrowhead Region, including Douglas County, Wisconsin

For

- **Minnesota Department of Employment and Economic Development (DEED)**
- **Minnesota Power**
- **Natural Resources and Research Institute (NRRI) University of Minnesota**
- **Iron Range Resources and Rehabilitation Board (IRRRB)**
- **Iron Mining Association of Minnesota**
- **Mining Minnesota**

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Bureau of Business and Economic Research

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The Bureau of Business and Economic Research extends a thank you to industry representatives from ArcelorMittal/Minorca Mine, Cardero, Cliffs Natural Resources, Duluth Metals, Encampment Minerals, Essar Steel Minnesota, Hibbing Taconite, Keetac, Kennecott Exploration, Magnetation, Mesabi Nugget, Mining Resources, Minntac, Northshore Mining, PolyMet, Teck American, Twin Metals, U.S. Steel, Vermillion Gold, United Taconite, and others for their willingness to provide information. The BBER also thanks Minnesota State representatives from the Department of Natural Resources, the Department of Revenue, and the Department of Employment and Economic Development, along with the University of Minnesota Natural Resources Research Institute for their assistance with fact-finding and background information.

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Executive Summary

The University of Minnesota Duluth Labovitz School of Business and Economics' research bureau, the Bureau of Business and Economic Research (BBER), was asked to study and report the direct, indirect, and induced economic impacts of construction and operations activities of ferrous and non-ferrous mining in Northeast Minnesota, measured in employment, output, and value added. (This report defines impact terminology in Section II—Impact Procedures and Input Assumptions.) IMPLAN Version3 software and data are used for the impact modeling. The study areas for the impact were designated as the State of Minnesota, and the counties of Minnesota's Arrowhead Region and Douglas County, Wisconsin.

BBER also studied Minnesota's ferrous and non-ferrous mineral revenue collected as taxes, royalties, and fees that were distributed in Minnesota.

All ferrous modeling in this analysis uses iron ore mining to represent Minnesota and Douglas County, Wisconsin, ferrous mining; all non-ferrous modeling in this analysis uses copper, nickel, lead, and zinc mining to represent Minnesota and Douglas County, Wisconsin, non-ferrous mining.[1] Also, the following mining impacts do not include other IMPLAN sectors classified as mining and described as "Stone mining and quarrying," and "Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying."

In this report, ferrous mining activities are referred to as Iron ore mining, following the IMPLAN industry description. In the same way, non-ferrous mining activities are referred to as copper, nickel, lead, and zinc mining. Although lead and zinc mining are not significant in Minnesota and Douglas County, Wisconsin, this model sector captures the copper and nickel impacts that are significant. The activities of the non-ferrous IMPLAN sector follows the NAICS definition for this industry and includes establishments primarily engaged in developing the mine site, mining, and preparing and concentrating ores valued chiefly for their copper, nickel, lead, or zinc content.

The most recent IMPLAN data available is for the year 2010. (IMPLAN data uses various federal sources, and inputs to the modeling were provided by industry representatives, as described in the report.) A baseline model for mining operations in 2010 was created to show the impact of current ferrous and non-ferrous mining in the State and region. Further models were built to estimate the additional impact of proposed expansions to current operations as well as the impact of new projects. (All impacts are reported in 2012 dollars.)

[1] Inputs for the non-ferrous group projects were gathered from industry representatives from Duluth Metals, Twin Metals, Encampment Minerals, Cardero, Kennecott, PolyMet, Teck-American, and Vermillion Gold.

Key Results

The results of the impact study, totaling expansions and new projects in addition to all on-going operations in Minnesota, for ferrous and non-ferrous mining, are as follows.

Ferrous and Non-ferrous Operations Impacts on Minnesota, Baseline 2010, and Proposed Expansions and New Projects[2]

Source: IMPLAN

			Direct Effect	*Indirect Effect*	*Induced Effect*	*Total Effect*
1)	**2010 Ferrous (Baseline)**	***Value Added***	$1,136,832,423	$349,036,421	$435,339,232	$1,921,208,076
		Output	$1,711,897,209	$602,940,089	$708,088,618	$3,022,925,917
		Employment	3,975	2,273	4,978	11,226
2)	**2010 Non-Ferrous (Baseline)**	***Value Added***	$111,689,936	$20,769,592	$24,596,460	$157,055,988
		Output	$136,398,301	$33,685,684	$40,004,310	$210,088,295
		Employment	175	144	232	551
3)	**Ferrous Expansions and New Projects**	***Value Added***	$1,628,764,657	$500,072,160	$623,720,164	$2,752,556,981
		Output	$2,452,672,657	$863,845,522	$1,014,494,252	$4,331,012,432
		Employment	5,029	2,875	6,297	14,201
4)	**Non-Ferrous New Projects**	***Value Added***	$115,785,590	$21,531,208	$25,498,408	$162,815,205
		Output	$141,400,005	$34,920,930	$41,471,260	$217,792,195
		Employment	427	352	566	1,345
5)	**Total Ferrous (Expansions, New Projects, and 2010 Baseline Operations)**	***Value Added***	$2,765,597,080	$849,108,581	$1,059,059,396	$4,673,765,057
		Output	$4,164,569,866	$1,466,785,611	$1,722,582,870	$7,353,938,349
		Employment	9,004	5,148	11,275	25,427
6)	**Total Non-Ferrous (New Projects and 2010 Baseline Operations)**	***Value Added***	$227,475,526	$42,300,800	$50,094,868	$319,871,193
		Output	$277,798,306	$68,606,614	$81,475,570	$427,880,490
		Employment	602	496	798	1,896
7)	**Total Ferrous and Non-Ferrous (Expansions, New Projects, and 2010 Baseline Operations)**	***Value Added***	$2,993,072,606	$891,409,381	$1,109,154,264	$4,993,636,250
		Output	$4,442,368,172	$1,535,392,225	$1,804,058,440	$7,781,818,839
		Employment	9,606	5,644	12,073	27,323

The above table shows that total economic impacts, from the largest possible increase in ferrous and non-ferrous mining production for the State of Minnesota are a Value Added total of almost $5 billion, and Output total of almost $7.8 billion, and an Employment total of more than 27,300.

[2] Definitions for interpreting this table are as follows.

Three measures: **Value Added**–A measure of the impacting industry's contribution to the local community in wages, rents, interest, and profits; **Output**–Represents the value of local production required to sustain activities; **Employment**–Estimates are in terms of full and part time jobs, not in terms of full-time equivalent employees.

Three impact effects: **Direct**–Initial spending in the study area resulting from the project; **Indirect**–The additional inter-industry spending from the direct impact; **Induced**–The impact of additional household expenditure resulting from the direct and indirect impact.

- **Existing <u>ferrous</u> mining industry contributions to Minnesota's economy**

Source: *IMPLAN, BBER*

Iron ore mining:	Minnesota Direct, Indirect, and Induced Total Effect			Arrowhead and Douglas County, Wisconsin Direct, Indirect, and Induced Total Effect		
Operations	***Value Added***	***Output***	***Employment***	***Value Added***	***Output***	***Employment***
2010 Baseline	$1,921,208,076	$3,022,925,917	11,226	$1,631,590,282	$2,492,315,978	8,795

— Using the base year of 2010, the IMPLAN model's Value Added total impact shows that iron-ore mining contributed more than $1.9 billion in wages, rents, interest, and profits to Minnesota's economy. This total represents the direct value, plus additional inter-industry spending that resulted from the direct, as well as additional household spending that resulted from the direct and inter-industry spending.

— The Output total shows that iron-ore mining produced more than $3 billion in local production required to sustain activities. This total represents the direct value, plus additional inter-industry spending resulting from production, as well as additional household spending resulting from direct and inter-industry spending.

— The Employment total of more than 11,000 full- and part-time jobs represents the direct employment plus other jobs dependent on the sector, as well as jobs created by the additional household spending linked to direct and indirect jobs in the iron-ore mining industry.

The IMPLAN input-output model also provides an opportunity to calculate a multiplier value associated with each of these measures (Value Added, Output, and Employment). For example, the employment multiplier for iron-ore mining in the State of Minnesota of 2.8 estimates that for every job in the iron-ore mining industry, another 1.8 jobs are created elsewhere in the economy. In the same way, the model estimates that for every dollar of wages, rents, interest, and profits, another $0.69 is generated throughout the economy of the State.

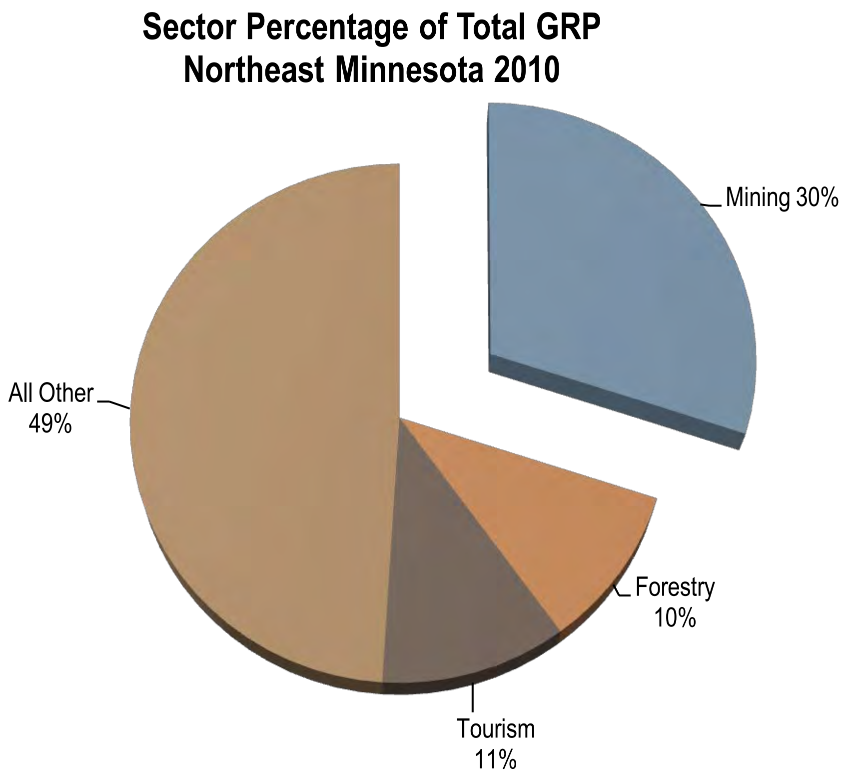
The impact of mining employment and the payroll associated with these jobs may be the most obvious impacts. However, an Output measure can show contribution to the region and to the State, through production taxes, royalties, and fees on the exported ore.

Although the total economic impacts for the State are always greater than the impacts for the region, the importance of the mining sector to the region's economy is proportionately greater.

From a regional point of view, for the period from 2004 to 2010, compared to other sectors of the economy in Northeast Minnesota, mining has led all other sectors contributing to Gross Regional Product (GRP). (See the report for details.) Note that the GRP for the State of Minnesota was $281.1 billion. When compared to the State, mining GRP totals approximately 5.3% for 2010.

Figure 1: NE Minnesota Percentage Gross Regional Product (GRP) by Industry Sector

Source: *IMPLAN, BBER*



- **Potential additions to <u>ferrous</u> mining expansions and new projects to the State's economy, if and when full operations are reached**

Source: IMPLAN, BBER

Iron ore mining: *Operations*	Minnesota Direct, Indirect, and Induced Total Effect *Value Added*	*Output*	*Employment*	Arrowhead and Douglas County, Wisconsin Direct, Indirect, and Induced Total Effect *Value Added*	*Output*	*Employment*
2010 Baseline	$1,921,208,076	$3,022,925,917	11,226	$1,631,590,282	$2,492,315,978	8,795
Expansions, 2016	$2,752,556,981	$4,331,012,432	14,201	$2,337,615,098	$3,570,795,747	11,127

For the following impacts, it is assumed that all currently proposed expansions and new projects in the ferrous mining industry sector are brought to full operations. These impacts are in addition to regular ferrous mining operations (but do not include construction impacts).

— The Value Added total impact shows that Iron ore mining expansions and new projects could contribute almost $2.8 billion in wages, rents, and profits annually as an addition to Minnesota's economy.

— The Output total impact shows that Iron ore mining expansions and new projects could contribute over $4.3 billion annually in local production as an addition to Minnesota's economy.

— The Employment total impact shows that Iron ore mining expansions and new projects could contribute more than 14,000 indirect and induced jobs (including temporary, part-time or short-term) in Minnesota employees by the impact year 2016.

Again, the total economic impacts for the State are always greater than the impacts for the region, although the importance of the mining sector to the region's economy is proportionately greater.

Construction in the Iron ore mining sector is estimated to occur between 2012 and 2016. The economic impact of the construction phase of all currently proposed expansions and new projects in the ferrous mining industry sector could contribute the following impacts for Minnesota:

Ferrous Mining Construction, Projected 2012–2016 Totals

Source: IMPLAN	*Value Added*	*Output*	*Employment*
2012	$744,837,822	$1,454,261,964	1,964
2013	$687,678,567	$1,342,661,101	3,079
2014	$138,277,993	$269,981,487	587
2015	$159,972,225	$312,329,163	1,258
2016	$100,988,119	$197,174,708	1,020

— For peak year construction (2012), the Value Added total impact shows that Iron ore mining construction could contribute almost $745 million in wages, rents, and profits to Minnesota's economy.

— For peak year construction, the Output total shows that Iron ore mining construction could contribute almost $1.5 billion in local production as part of Minnesota's economy.

— For peak year construction, the Employment measure shows that Iron ore mining construction could employ nearly 2,000 employees in direct, indirect, and induced jobs (including temporary, part-time or short-term) in Minnesota.

During 2011 (calendar year), Minnesota's iron mines paid $151.9 million in Production Tax, Occupation Tax, Sales and Use Tax, Income Tax, various Ad Valorem and Property Taxes, and Royalties and Rentals on State minerals.

Ferrous Mining Mineral Receipts, Minnesota, 2011

Source: *MN Depart. Of Revenue, MN DNR*	*2010 taxes payable in 2011*
Taconite Production Tax	$79,138,000
Occupation Tax	$12,617,000
Sales and Use Tax	$17,101,895
Income Tax (withholding on private royalties)	$137,943
Various Ad Valorem and Property Taxes	$902,235
Royalties and Rentals on State Iron Ore	
School Trust Lands	$25,696,263
University Trust Lands	$15,029,345
Tax Forfeit	$1,021,737
Other State Accounts	$277,000
Total	**$151,921,418**

The 2010 taconite production tax of more than $79 million is payable the following year.

In order to interpret tax tables in this report, readers should note that taxes are distributed between the General Fund, local units of government, and education. A further detail on interpreting the occupation tax is to note that this tax is split according to 10% for the University of Minnesota, 40% to Elementary and Secondary Education, and 50% to the General Fund. (A further breakdown of this $79 million in Production tax is found in Appendix A.)

Ferrous mining tax impacts have special importance for the support of schools and higher education in Minnesota. During 2011 (calendar year), Minnesota's iron mining industry paid $64.1 million towards Minnesota's education, through a percentage of production taxes, royalties and rents, and occupation taxes.

Ferrous Mining Mineral Receipts Specifically in Support of Education, Minnesota, 2011

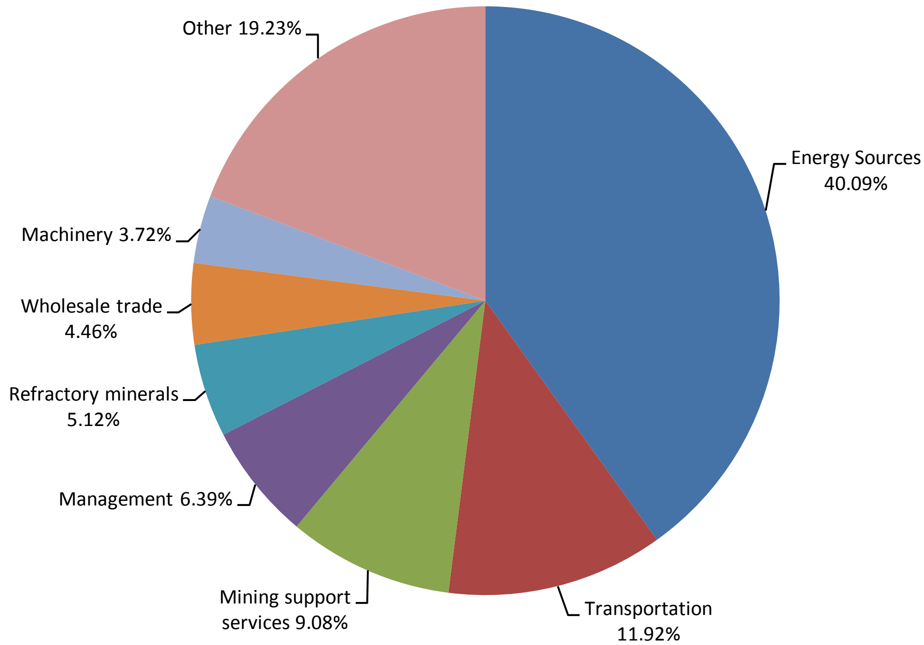
Source: *MN Depart. Of Revenue, MN DNR*	*School*	*University*	*Total Education*
School district component of Production Tax	$17,094,176		$17,094,176
State iron ore royalties and rent	$25,696,263	$15,029,345	$40,725,608
Occupation Tax	$5,046,800	$1,261,700	$6,308,500
Totals	**$47,837,239**	**$16,291,045**	**$64,128,284**

- **<u>Ferrous</u> mining suppliers and their contributions to mining production**

Based on the model's regional inputs from the industry balance sheet, the following are the ferrous mining industry's local purchases from suppliers. Support for these industries translates into development of the State's mining industry.

Figure 2: Local Supplier Purchases

Source: *IMPLAN, BBER*



In the chart above, Energy Sources include Electric Power, Natural Gas, and Petroleum. The section of Transportation includes both transports by truck and by rail.

- **Existing <u>non-ferrous</u> mining additions to Minnesota's economy**

Source: IMPLAN, BBER

Copper, nickel, lead, and zinc mining:	Minnesota Direct, Indirect, and Induced Total Effect			Arrowhead and Douglas County, W Direct, Indirect, and Induced Total Effect		
Operations	***Value Added***	***Output***	***Employment***	***Value Added***	***Output***	***Employment***
2010 Baseline	$157,055,988	$210,088,295	551	$154,976,119	$194,830,341	507

— Using the 2010 base year model (operations in the year 2010), the Value Added total impact shows that copper, nickel, lead, and zinc mining contributed more than $157 million in wages, rents, and profits to Minnesota's economy. (This figure represents the value received from exploration and supporting industries.)

— The Output total impact shows copper, nickel, lead, and zinc mining produced over $210 million in local production as part of Minnesota's economy.

— The Employment total impact shows that copper, nickel, lead, and zinc mining directly and indirectly employed 551 employees (including temporary, part-time or short-term jobs) in

Minnesota.

- **Potential additions to non-ferrous mining expansions and new projects to the State's economy, if and when full operations are reached**

Source: IMPLAN, BBER

Copper, nickel, lead, and zinc mining:	Minnesota Direct, Indirect, and Induced Total Effect			Arrowhead and Douglas County, Wisconsin Direct, Indirect, and Induced Total Effect		
Operations	***Value Added***	***Output***	***Employment***	***Value Added***	***Output***	***Employment***
2010 Baseline	$157,055,988	$210,088,295	551	$154,976,119	$194,830,341	507
New Projects, 2016	$162,815,205	$217,792,195	1,345	$160,659,059	$201,974,731	1,235

For the following impacts, it is assumed that all currently proposed new projects in the non-ferrous mining industry sector are brought to full operations. These impacts are in addition to regular non-ferrous mining operations (but do not include construction impacts).

— The Value Added total impact shows that copper, nickel, lead, and zinc mining new projects could contribute almost $163 million in wages, rents, interests and profits annually as an addition to Minnesota's economy.

— The Output total impact shows that copper, nickel, lead, and zinc mining new projects could contribute almost $218 million annually in local production as an addition to Minnesota's economy.

— The Employment total impact shows that copper, nickel, lead, and zinc mining new projects could contribute more than 1,300 additional direct, indirect, and induced jobs (including temporary, part-time or short-term) in Minnesota by the impact year 2016.

The economic impact of the construction phase of all currently proposed new projects in the non-ferrous mining industry sector could contribute the following impacts:

Non-Ferrous Mining Construction, Impacts on the State of Minnesota, 2012-2016

Source: IMPLAN	***Value Added***	***Output***	***Employment***
2012	—	—	—
2013	—	—	—
2014	$157,541,469	$307,592,556	1,020
2015	$157,541,469	$307,592,556	1,020
2016	$560,181,099	$1,093,728,114	2,170

— For peak year construction (2016), the Value Added total impact shows that copper, nickel, lead, and zinc mining construction could contribute over $560 million in wages, rents, interest and profits to Minnesota's economy.

— For peak year construction (2016), the Output total impact shows that copper, nickel, lead, and zinc mining construction could contribute almost $1.1 billion in production as part of

Minnesota's economy.

— For peak year construction (2016), the Employment total impact shows that copper, nickel, lead, and zinc mining construction could employ more than 2,100 employees in direct, indirect, and induced jobs (including temporary, part-time or short-term) in Minnesota.

In order to report non-ferrous taxes in Minnesota, the BBER followed the Minnesota DNR's Mineral Receipts by Account for 2010 and 2011. Compared to ferrous mining, non-ferrous mining contributes much less to the State.

- **Less than full operations of ferrous and non-ferrous proposed expansions and new projects**

The BBER considered the possibility that only some of the proposed projects will progress to full operations status. The following table presents impact results assuming 75% of Value Added, 75% of Output, and 75% of Employment is achieved by year 2016. The table also shows values for assuming 50% of projects are achieved and for the baseline operations in 2010 (for comparison).

Ferrous and Non-Ferrous Mining Impact on Minnesota: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$2,915,372,186	$4,548,804,627	15,546
75%	$2,186,529,140	$3,411,603,470	11,660
50%	$1,457,686,093	$2,274,402,314	7,773
Baseline (2010)	$2,078,264,064	$3,233,014,212	11,777

Note: Although the current economic downturn may affect the estimates of start dates and other time line assumptions, the BBER assumes in this study, following indications from industry, that these projects are proceeding as planned, and that the proposed projects are attempting to emerge from the downturn without losing years of momentum.

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The Economic Impact of Ferrous and Non-Ferrous Mining on the State of Minnesota and on the Arrowhead Region, including Douglas County, Wisconsin

I. Project Description

This project assesses the economic impact of ferrous and non-ferrous mining in Northeast Minnesota on the economy of the State of Minnesota and on the Arrowhead Region that, for this report, includes Douglas County, Wisconsin. Normally, Douglas County is not considered part of the Arrowhead Region, but since the taconite is transported through it, it is being included in this study.

The UMD Labovitz School of Business and Economics' research bureau, the Bureau of Business and Economic Research (BBER), studied and estimated the economic impacts of ferrous and non-ferrous mining construction and operations in Northeast Minnesota. The BBER has previously studied and reported a similar analysis of the ferrous and non-ferrous mining in Northeastern Minnesota in 2009. Additionally, it has studied and reported the prospective regional socio-economic impacts of a project in Menominee County, Michigan, in 2010; the economic impact of Essar Steel Minnesota in 2010; and the economic impact of U.S. Steel's Keetac mine expansion in 2009. Several further analyses, studies, and reports for the mining industry by the BBER were also conducted in 2006 and 2003.

The economic modeling data and software used for this project was IMPLAN, version 3.0, created in Minnesota by MIG, Inc. The study used IMPLAN's economic multiplier analysis and input/output modeling with the most recent IMPLAN data, which is for year 2010. Results of modeling are presented here in a written report.

The research objectives of the study included:

— To study the recent economic activity of ferrous and non-ferrous mining industries in Northeast Minnesota, including employment and production in unit tons.

— To model construction and operations impacts using three measures and three effects of mining activity. This will include the measures of employment, output, and value added, and will also model direct, indirect, and induced economic effects in the economies of the State of Minnesota, and the Arrowhead Region including Douglas County, Wisconsin.

— To describe Minnesota's mineral revenue collected from ferrous and non-ferrous mining industries in Northeast Minnesota, including 1) production taxes, 2) occupation taxes and royalties, 3) sales and use taxes, and 4) a discussion of how mineral revenue is being spent by the State of Minnesota.

— To draft the findings of the impact analysis into a report.

Modeling

The BBER needed inputs from companies involved in mining construction and estimates for construction project start dates and estimates of full operations.

Models were created to include projects, such as Essar's (Minnesota Steel) plant construction and the Mesabi Nugget project, as well as individual non-ferrous proposed projects like PolyMet. The construction impact model years were designated to begin with 2012. BBER's modeling used the completion date supplied by companies involved for any new project.

Operations models were created to include mining impacts from years beginning with 2012. The full operations year, when construction is complete and all projects are fully operational, was determined to be 2016.

Some IMPLAN modeling issues associated with small study areas like that in this report of county-level impacts, as noted in the IMPLAN User's Guide[3] include the following:

A small area will have a high level of leakage. Leakages are any payments made to imports or value added sectors, which do not in turn re-spend the dollars within the region.

Also, it can be expected that input-output multipliers are larger when more economic activity is incorporated into the local transactions matrix. The more imports are internalized, the larger the calculated multipliers become. At the state level all counties are incorporated, and for the state, the greatest level of internalized economic activity is attained. Theoretically, therefore, the state IMPLAN multipliers will always be greater than multipliers for any individual or subset of counties. But, as with most theories, this one has exceptions. It is possible, for example, for the same impact run on both a state and county models to yield lower impact results in the state model compared to the county model. It does not happen that frequently, but it is possible.

Deliverables

1) The BBER will report the direct, indirect, and induced economic impacts of construction and operations activities of ferrous and non-ferrous mining in Northeast Minnesota, measured in employment, output, and value added.
2) The BBER will report a description of the Northeast Minnesota mining industries in terms of a global mining context.
3) The BBER will report Minnesota's mineral revenue collected from ferrous and non-ferrous mining industries in Northeast Minnesota, including 1) production taxes, 2) occupation taxes and royalties, and 3) sales and use taxes.
4) The BBER will report ferrous and non-ferrous mineral revenue spent by the State of Minnesota.

[3] IMPLAN is used by state governments and the USDA Forest Service, among others. See MIG, Inc., IMPLAN System (data and software), MIG, Inc. 502 2nd St., Ste 301, PO Box 837, Hudson, WI 54016-1543. www.implan.com

5) The BBER will draft a final written report that will present the findings and analysis.

6) The BBER will offer an oral PowerPoint presentation of the BBER findings, if so requested.

Study Area

The geographic scope for this economic impact analysis is proposed to be the Arrowhead region of Minnesota and the State of Minnesota. The Arrowhead Region of Northeast Minnesota includes Aitkin, Carlton, Cook, Itasca, Koochiching, Lake, and St. Louis Counties. For this study, it also includes Douglas County in Wisconsin.

The BBER worked closely with mining companies, the Iron Range Resources and Rehabilitation Board, the Minnesota Department of Employment and Economic Development, the Minnesota Department of Natural Resources—Lands and Minerals Division, and the University of Minnesota Natural Resources Research Institute, as well as the Iron Mining Association of Minnesota and Mining Minnesota and others, in determining key assumptions in the development of the IMPLAN models. Inputs required for these models include average employment for each year during any construction periods and dollar cost on a year-by-year basis for such construction periods. Operating assumptions required for the models include employment estimates, local purchases, and operations dollar value of sales or output production.

Regional data for the impact models for value added, employment, and output measures have been supplied by IMPLAN for this impact. Employment assumptions were provided to the BBER to enable construction of the impact model. From these data, Social Accounts, Production, Absorption, and Byproducts information were generated from the national level data and were incorporated into the model. All region study definitions and impact model assumptions were agreed on before work with the models began.

Figure 3. Counties of Minnesota's Arrowhead Region and Douglas County, Wisconsin

As background, the BBER estimated a simplified industry sector percentage of Gross Regional Product (GRP) for the major sectors of the Northeast Minnesota economy. Mining in the Arrowhead Region and for the Duluth Metropolitan Statistical Area has been the leading industrial sector of the economy. Note that the GRP for the State of Minnesota was $281.1 billion. When compared to the State, mining GRP totals approximately 5.3% for 2010. However, comparing Northeast Minnesota economic activity by sector, GRP for mining shows that over time, mining has been the leading industrial sector, and that the mining industry has increased in relative importance.

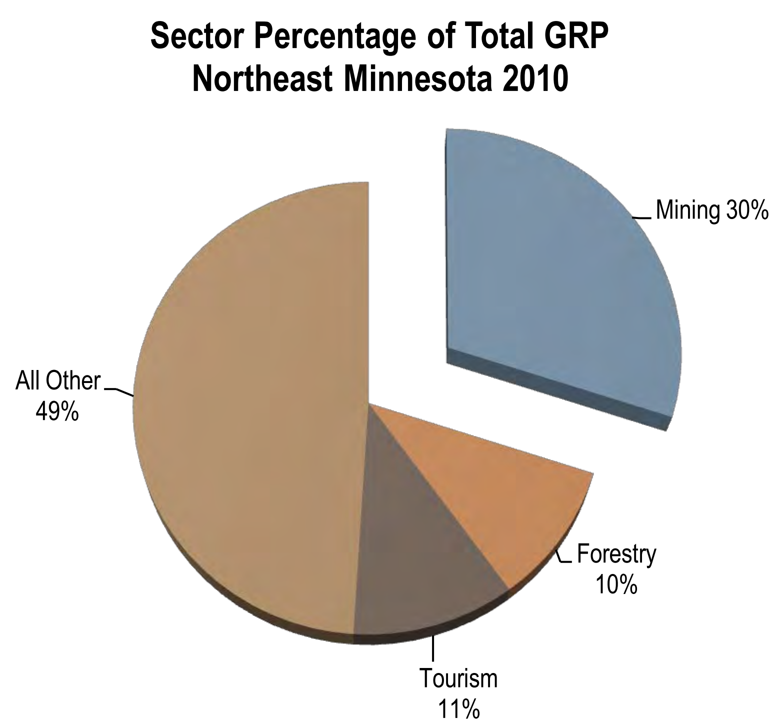
Table 1. Sector Percentages of Total GRP in Billions, Northeast Minnesota 2010

Industry	*2004*	*% of Total*	*2006*	*% of Total*	*2007*	*% of Total*	*2010*	*% of Total*
Mining	3.1	26%	3.9	30%	4.7	34%	4.5	30%
Forestry	1.9	16%	1.8	14%	1.6	12%	1.5	10%
Tourism	1.3	11%	1.4	11%	1.5	11%	1.6	11%
All Other	5.6	47%	5.2	45%	5.9	43%	7.3	49%
Total	11.9	100.0%	12.3	100.0%	13.7	100.0%	14.9	100.0%

Source: J. Skurla, UMD Labovitz School of Business and Economics, Bureau of Business and Economic Research
See also U.S. BEA at http://www.bea.gov/bea/regional/gsp/
Note: Tourism is estimated from the IMPLAN sectors, "amusements, gambling, and recreation," and "accommodation and food services." Also note: The above estimated GRP for an industry sector (for example, mining) includes estimations for indirect and induced effects (such as healthcare) provided to the industry.

From 2004 to 2010, mining has contributed to the GRP by almost three times that of the Forestry and Tourism sectors of the economy in Northeast Minnesota.

Figure 4. NE Minnesota Percentage Gross Regional Product (GRP) by Industry Sectors



II. Impact Procedures and Input Assumptions

IMPLAN Models

There are two components to the IMPLAN system, the software and databases. The databases provide all information to create regional IMPLAN models. The software performs the calculations and provides an interface for the user to make final demand changes. IMPLAN software version 3.0 was used in this analysis.

Comprehensive and detailed data coverage of the IMPLAN study areas by county, and the ability to incorporate user-supplied data at each stage of the model building process, provides a high degree of flexibility both in terms of geographic coverage and model formulation—in this case, definition of the State of Minnesota, and the Arrowhead region including Douglas County, Wisconsin, as a study area, and the definition of specific models for construction and operations, with adjusted production functions to reflect the proposed plant expansion. Using the IMPLAN software and data, the BBER identified the industry's proposed expenditures in terms of the sectoring scheme for the model, in producer prices, in historical dollars based on the year of the model, and applied those dollars spent within the study area definition given for the impact analysis.

Data

IMPLAN data files use federal government data sources including:

- US Bureau of Economic Analysis Benchmark I/O Accounts of the US
- US Bureau of Economic Analysis Output Estimates
- US Bureau of Economic Analysis REIS Program
- US Bureau of Labor Statistics County Employment and Wages (CEW) Program
- US Bureau of Labor Statistics Consumer Expenditure Survey
- US Census Bureau County Business Patterns
- US Census Bureau Decennial Census and Population Surveys
- US Census Bureau Economic Censuses and Surveys
- US Department of Agriculture Crop and Livestock Statistics

IMPLAN data files consist of the following components: employment, industry output, value added, institutional demands, national structural matrices and inter-institutional transfers.

Impacts for this model use the most recent IMPLAN data available, which is for the year 2010. The impact is reported in 2012 dollars.

Economic impacts are made up of direct, indirect, and induced impacts. The following cautions are suggested assumptions for accepting the impact model:

- IMPLAN input-output is a production-based model.
- Local or export based purchases that represent transfers from other potential local purchases are not counted.

- The numbers (from U.S. Department of Commerce secondary data) treat both full and part-time individuals as being employed.
- Assumptions need to be made concerning the nature of the local economy before impacts can be interpreted.
- The IMPLAN model was constructed for the year 2010 (most recent data available).

Definitions Used in This Report

The IMPLAN models for both operations and construction use the following definitions for the three measures and three effects of the impact reports:

Measures

Value Added – A measure of the impacting industry's contribution to the local community; it includes wages, rents, interest and profits.

Output–Represents the value of local production required to sustain activities.

Employment – Estimates are in terms of jobs, not in terms of full-time equivalent employees. Hence, these may be temporary, part time or short term jobs.

Effects

Direct – Initial spending in the study area resulting from the project

Indirect – The additional inter-industry spending from the direct impact

Induced – The impact of additional household expenditure resulting from the direct and indirect impact.

Industry Definitions

IMPLAN models for this study used the industrial sector 22 (Iron ore mining) to model the impact of ferrous mining. IMPLAN provides a bridge table, which identifies the corresponding Bureau of Economic Analysis (BEA) sector, as well as the North American Industry Classification (NAICS) code equivalents.

Table 2. Ferrous Mining Industry Definition

IMPLAN Sector	*Description*	*BEA*	*NAICS*
22	Iron ore mining	21221	21221

IMPLAN models for this study used the industrial sector 23 (copper, nickel, lead, and zinc mining) to model the impact of non-ferrous mining.

Table 3. Non-Ferrous Industry Definition

IMPLAN Sector	*Description*	*BEA*	*NAICS*
23	Mining copper, nickel, lead, and zinc	21223	21223

IMPLAN sector 24 corresponds to NAICS codes 21222 for mining non-ferrous metals gold and silver, and 21229 for Other Metal Ore Mining (including uranium-radium-vanadium ores, molybdenum ores, antimony ores, columbium ores, ilmenite ores, magnesium ores, tantalum ores and tungsten ores) which are not currently included in the business models for projects proposed for Minnesota, and are therefore not included in the non-ferrous sector for this study.

Mining impacts in this report have been sectored for analysis as ferrous and non-ferrous and do not include other IMPLAN sectors classified as mining, such as "Stone mining and quarrying," and "Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying." Excluded sectors include such activities as "Stone mining and quarrying," "Dimension stone mining and quarrying," "Crushed and broken limestone mining," "Crushed and broken granite mining," "Other crushed and broken stone mining," "Sand, gravel, clay, and refractory mining," "Construction sand and gravel mining," "Industrial sand mining," and "Clay, ceramic, and refractory minerals mining."

Ferrous mining activities in this report are modeled in IMPLAN sector 22, and the sector is referred to as "Iron ore mining" in the text following the designation of the IMPLAN industry description. The same is true for non-ferrous mining activities, which are referred to in this report by the IMPLAN sector description "Mining copper, nickel, lead, and zinc." Although lead and zinc mining is not significant in Minnesota, the model sector "Mining copper, nickel, lead, and zinc" captures the copper and nickel impacts, which are significant.

The impact of mining exploration and drilling, identified under NAICS industry code 213 (Support Activities for Mining), are not the focus of this impact, although these activities are accounted for in the IMPLAN model, specifically through IMPLAN sector 27 (Other nonmetallic mineral mining and quarrying) and sector 30 (Support activities for other mining).

Model Assumptions

- Construction years for various projects are staggered between 2012 and 2016. Construction impacts are reported by years 2012, 2013, 2014, 2015, and 2016 and include all projects active during the reporting year.
- The operations year for all has been determined to be 2016. This impact study recognizes the broadest number of possible ferrous expansion projects, as well as start-ups in ferrous and non-ferrous mining.
- All impacts are reported in 2012 dollars.

Special considerations for interpreting these impact numbers include the following cautions:

Regional indirect and induced effects are driven by assumptions in the model. One problem is that the assumptions can mask the true multiplier. This is especially true of the assumption of constant returns to scale: This assumption most affects induced effects and says that if I drink coffee, and my income increases, I will drink proportionally more than before. The amount of weight placed on the induced effects (the percentage of the total induced effect you would want to use) could be further analyzed with an in-depth impact study, involving much more specific data collection and more detailed analysis.

The BBER suggests caution in regard to the interpretation of the tax impacts from these projects: Tax law changes frequently and will be difficult to forecast through the years proposed as operations for these projects. Also, taxes impacts in this report are based on different formulations. For instance, it has been suggested that occupation taxes could be expected to decrease.

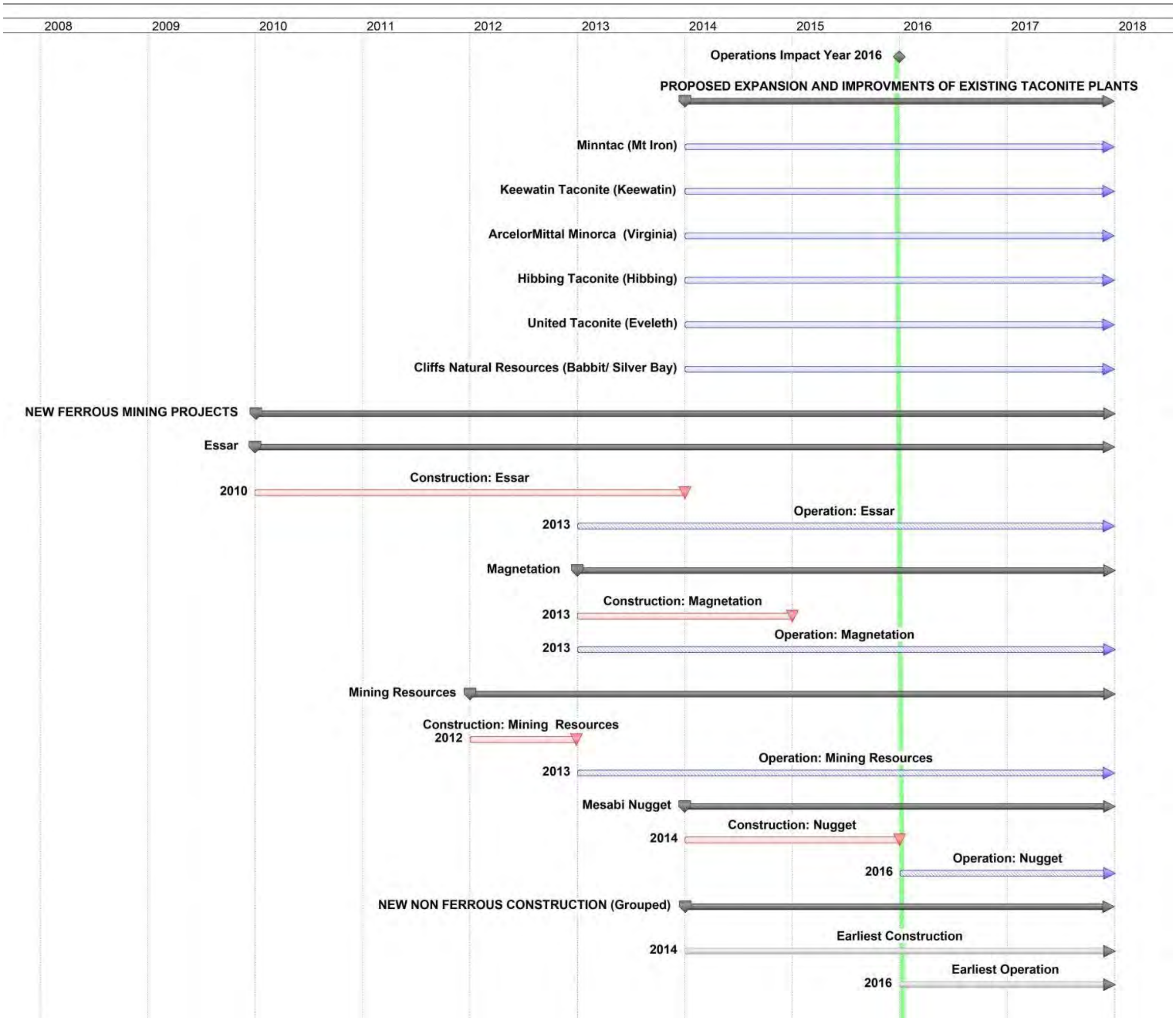
Readers should also note that estimated changes in production technology and employee productivity for industry sectors can differ; for instance, a difference in output per worker for differing industry sectors when production modeling includes Iron ore mining and Iron and steel mills.

Finally, and most importantly, the relationship of Output to Employment has been set for the model by data provided by the project managers to the BBER; the modeling in this study is driven by inputs provided to the models by the best estimates of engineers and managers involved in each project. It can be noted that, for purposes of research and with more resources, the modeling methodology can be driven by data collected from surveys and post-construction values. This survey data can provide greater accuracy in regional impact assessments for the linkage between core and peripheral labor market areas, and deliver better estimates of local vs. regional purchases.

Project Time Lines and Selection of Impact Year

A time line was used in order to select an appropriate year for the industry sector's full operations impact (YR 2016). A significant factor influencing assumptions about construction and operations start dates is the time necessary to complete the Environmental Impact Statement and all permitting activity that must be completed before construction can begin. The BBER has not attempted to forecast how long each project's permitting might require to complete. Also note, for purposes of display in this report, the BBER has grouped the non-ferrous start-ups to indicate the earliest construction and operations start date that might be assumed. The time line can be found on the following page. Note: At the time of this report, there were no non-ferrous projects poised for construction. These projects were only in exploration phase. The timing of non-ferrous project construction and then operations is difficult to determine or estimate. The slow economic recovery and possible difficulty in obtaining equity and debt financing from financial markets have delayed many of the projects.

Figure 5. The BBER's Assumptions for Project Time Lines and Selection of Impact Year 2016*



* As noted above, this time line was used in order to select an appropriate year for the industry sector's full operations impact (YR 2016). A significant factor influencing assumptions about construction and operations start dates is the time necessary to complete the Environmental Impact Statement and all permitting activity that must be completed before construction can begin. The BBER has not attempted to forecast how long each project's permitting might require to complete. Also note, for purposes of display in this report, the BBER has grouped the non-ferrous start-ups to indicate the earliest construction and operations start date that might be assumed.

III. Findings: Ferrous Mining Impacts

In this section, the BBER reports the direct, indirect, and induced economic impacts of construction and operations activities of ferrous mining in Northeast Minnesota, measured in employment, output, and value added. Impacts are modeled for both the State of Minnesota, and the immediate region, including the counties of the Arrowhead Region and Douglas County, Wisconsin.

To provide a baseline reference, the BBER modeled the impact on the State's economy that might be felt if ferrous mining and all its transactions had been removed from the State of Minnesota. The BBER uses IMPLAN's most recent data, which is for year 2010, for this impact model. This provides insight into the contribution of the ferrous mining industry to the State's economy.

Next, using employment and output projections from the mining industry, as well as assistance from representatives of the State, the BBER modeled the economic impact of proposed expansions and projects in the ferrous mining industry sector. A special sub-section of the findings covers the results of modeling ferrous mining tax impacts.

Finally, the BBER considered the possibility that not all projects will be viable and will progress to full operations status. Therefore, impacts for two development scenarios are presented, to show impact results if only half or only three quarters of projects currently proposed succeed. The 75% and 50% impacts are shown in relation to the baseline data and full implementation scenarios.

Ferrous Mining Industry's Contribution to the State's Economy

IMPLAN provides a model of the economy of the State of Minnesota, including ferrous mining (identified as sector 22 Iron ore mining), as presented in the section "Industry Definitions," above. The values in the tables below are estimated from sources associated with the IMPLAN model and also identified above.

In the tables below, the Value Added total measure shows that Iron ore mining contributed more than $1.9 billion in wages, rents, and profits to Minnesota's economy. The Value Added total represents the direct value of the wages, etc., plus the additional inter-industry spending that resulted from these wages, plus any additional household spending that resulted from the direct wages and inter-industry spending.

The Output total measure shows that Iron ore mining produced more than $3 billion in local production as part of Minnesota's economy. The Output total represents the direct value of local production, plus the additional inter-industry transactions that resulted from local production, plus any additional household spending that resulted from inter-industry production.

The Employment measure shows that Iron ore mining directly employed more than 3,900 employees (jobs—including temporary, part-time or short-term) in Minnesota. The Employment total of more than 11,000 jobs represents the direct employment in the industry sector, plus other jobs dependent on, but not part of, the Iron ore mining sector, plus any jobs created by the additional household spending and activity linked to direct and indirect jobs in the Iron ore mining industry.

The IMPLAN input-output model also provides an opportunity to calculate a multiplier value associated with each of these measures. For example, the employment multiplier for Iron ore mining in the State of Minnesota of 2.8 indicates that for every job in the Iron ore mining industry, another 1.8 jobs are created as the indirect and induced effect of the mining industry's job. In the same way, the model estimates that for every dollar of wages, rents, interest and profits, another $0.69 is generated through indirect and induced effects throughout the economy of the State.

The impact of mining employment and the payroll associated with these jobs may be the most obvious impact; however the Output measure also shows contribution to the region and to the State through production taxes, royalties, and fees on the exported ore.

Although the total economic impacts for the State are almost always greater than the impacts for the Arrowhead Region and Douglas County, Wisconsin, the importance of the mining sector to the region's economy is proportionately greater.

The following tables show the baseline impact (current operations as of 2010) of ferrous mining on the State of Minnesota and the region, in 2012 dollars.

Table 4: Minnesota Ferrous Mining, Economic Impacts, Baseline 2010

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$1,136,832,423	$349,036,421	$435,339,232	$1,921,208,076
Output	$1,711,897,209	$602,940,089	$708,088,618	$3,022,925,917
Employment	3,975	2,273	4,978	11,226

Note direct effects for Value Added, Output, and Employment result in different totals for the State and the region. The regional economy does not enjoy the same level of added indirect and induced effects. This implies, for instance, that Iron ore mining creates about 2,400 more jobs in the Metro and other parts of the State compared to the Arrowhead region and Douglas County.

Table 5: Arrowhead and Douglas County, Wisconsin, Ferrous Mining, Economic Impacts, Baseline 2010

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$1,136,832,423	$230,153,874	$264,603,985	$1,631,590,282
Output	$1,711,897,209	$345,943,615	$434,475,153	$2,492,315,978
Employment	3,975	1,273	3,547	8,795

The top twenty-five Minnesota indirect and induced jobs dependent on Iron ore mining come from the following supporting industries:

Table 6: Iron Ore Mining Employment Impacts in Minnesota, Top Twenty-Five Detail, Baseline 2010

Source: IMPLAN

Industry	*Direct*	*Indirect*	*Induced*	*Total*
Mining iron ore	3,975	20	0	3,995
Food services and drinking places	0	37	519	556
Transport by truck	0	342	35	377
Real estate establishments	0	31	237	268
Wholesale trade businesses	0	125	141	266
Private hospitals	0	0	247	247
Electric power generation, transmission, and distribution	0	208	17	225
Offices of physicians, dentists, and other health practitioners	0	0	224	224
Nursing and residential care facilities	0	0	201	201
Nondepository credit intermediation and related activities	0	63	133	196
Retail Stores - General merchandise	0	8	172	180
Support activities for other mining	0	171	0	171
Retail Stores - Food and beverage	0	8	159	167
Management of companies and enterprises	0	140	26	166
Securities, commodity contracts, investments, and related activities	0	25	137	162
Employment services	0	57	88	145
Civic, social, professional, and similar organizations	0	18	109	127
Mining and quarrying sand, gravel, clay, and ceramic and refractory minerals	0	116	0	116
Individual and family services	0	0	107	107
Retail Stores - Motor vehicle and parts	0	8	97	105
Retail Nonstores - Direct and electronic sales	0	4	100	104
Monetary authorities and depository credit intermediation activities	0	28	73	101
Services to buildings and dwellings	0	36	56	92
Retail Stores - Miscellaneous	0	4	83	87
Architectural, engineering, and related services	0	67	17	84
Total From Top 25	**3,975**	**1,516**	**2,978**	**8,469**
As well as an additional 2,757 jobs in another 279 various sectors of the economy…	0	757	2,000	2,757
Grand Total	**3,975**	**2,273**	**4,978**	**11,226**

Jobs created as the impact of taxes are included in the model's calculations.

Economic Impact: Proposed Ferrous Mining Expansions and New Projects

The BBER modeled the economic impact of proposed expansions and projects in the ferrous mining industry sector. For this report, impact findings from individual projects are aggregated in the Iron ore mining sector and present an estimation of the impact of all currently proposed ferrous mining expansions and new start-up projects. The BBER relied on industry representatives and State of Minnesota representatives for its inventory of possible projects. The timeline in Figure 5 shows the BBER's rationale for choosing the year 2016, as the first possible full operations year in which all projects might be operational.

The BBER also modeled the economic impact of the total sector activity, which combines the proposed expansions and projects with the on-going industry in the State. Tables described as "all operations" present the impacts of Iron ore mining in year 2016 (in 2012 dollars), as if all proposed expansions and new projects were at full operations and are added to the continuing impact of current (2010) Iron ore mining operations.

Minnesota Construction: Proposed Ferrous Mining Expansions and New Projects

These projects include investment in facilities improvement and maintenance. Project totals have been aggregated by year. As noted earlier, the timeline for project construction is dependent on environmental permitting and the months or years such permitting requires for approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016. Note that unlike operations impacts, construction impacts do not present annual recurring totals. Each construction year's wages, production, and employment should be considered a snap-shot of a single year impact. Typically, construction is more labor and investment-intensive at the start of a project than in the final stages. In addition, although the construction investment adds up over time, employment does not; consider, for instance, that a construction project truck driver employed during 2012 may be continuing in the same job in 2013.

Table 7. Ferrous Mining Construction's Value Added, Output, and Employment Impacts on the State of Minnesota 2012–2016, Proposed Expansions and New Projects

Source: IMPLAN	***Value Added***	***Output***	***Employment***
2012	$744,837,822	$1,454,261,964	1,964
2013	$687,678,567	$1,342,661,101	3,079
2014	$138,277,993	$269,981,487	587
2015	$159,972,225	$312,329,163	1,258
2016	$100,988,119	$197,174,708	1,020

Minnesota Operations:
Proposed Ferrous Expansions and Mining Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all proposed expansions and new projects to be in year 2016.

Table 8. Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the State of Minnesota, 2016, Proposed Expansions and New Projects

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$1,628,764,657	$500,072,160	$623,720,164	$2,752,556,981
Output	$2,452,672,657	$863,845,522	$1,014,494,252	$4,331,012,432
Employment	5,029	2,875	6,297	14,201

Minnesota Operations:
All Proposed and Continuing Ferrous Mining, 2016

The table below shows the estimated impact of full operations for all proposed expansions and new projects and all continuing industry operations not considered a start-up or expansion of production capacity, for year 2016.

Table 9. Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the State of Minnesota, 2016, All Operations

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$2,765,597,080	$849,108,581	$1,059,059,396	$4,673,765,057
Output	$4,164,569,866	$1,466,785,611	$1,722,582,870	$7,353,938,349
Employment	9,004	5,148	11,275	25,427

Region Construction:
Proposed Ferrous Mining Expansions and New Projects

As with the impacts for the State, these projects include investment in facilities improvement and maintenance. Project totals have been aggregated by year. As noted earlier, the time line for project construction is dependent on environmental permitting and does not forecast the months or years such permitting requires for approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016.

Table 10. Ferrous Mining Construction's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, 2012–2016

Source: IMPLAN	*Value Added*	*Output*	*Employment*
2012	$541,798,194	$1,159,155,347	1,620
2013	$500,220,297	$1,070,201,130	2,540
2014	$100,583,985	$215,195,384	485
2015	$116,340,981	$248,906,845	1,038
2016	$73,459,178	$157,162,954	841

Region Operations:
Proposed Ferrous Mining Expansions and New Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all proposed expansions and new projects to be in year 2016.

Table 11. Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, Expansions and New Projects, 2016

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$1,628,764,657	$329,746,526	$379,103,915	$2,337,615,098
Output	$2,452,672,657	$495,641,041	$622,482,049	$3,570,795,747
Employment	5,029	1,611	4,487	11,127

Region Operations:
All Proposed and Continuing Ferrous Mining, 2016

The table below shows the estimated impact of full operations for all proposed expansions and new projects and all continuing industry operations not considered a start-up or expansion of production capacity, for year 2016.

Table 12. Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, 2016, All Operations

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$2,765,597,080	$559,900,400	$643,707,900	$3,969,205,380
Output	$4,164,569,866	$841,584,656	$1,056,957,202	$6,063,111,725
Employment	9,004	2,884	8,034	19,922

FERROUS MINING TAX IMPACTS

Ferrous Mining Tax Impacts on Minnesota and the Region

During 2011 (calendar year) Minnesota's iron mines paid $151.9 million in Production Tax, Occupation Tax, Sales and Use Tax, Income Tax, various Ad Valorem and Property Taxes and Royalties and Rentals on state minerals.

The 2010 taconite production tax of more than $79 million is payable the following year. As we note below, and in order to reconcile totals for subsequent tax impacts, readers must note that $97.3 million in Production, Sales and Use, Income and various Ad Valorem Taxes were accrued in 2010. These taxes are spread between the General Fund, local units of government and schools. Approximately $17.1 million of this was support to local school districts. (See Table 14.) A further detail on interpreting the Occupation tax is to note that the occupation tax is split according to 10% for the University of Minnesota, 40% to Elementary and Secondary Education, and 50% to the General Fund (or $6,308,500 in 2010). A further breakdown of this $79 million is found in Appendix A.

Table 13. Minnesota's Iron Mines Direct Support for the State

Source: *MN Depart. Of Revenue, MN DNR*	*2010 Taxes Payable in 2011*
Taconite Production Tax	$79,138,000
Occupation Tax	$12,617,000
Sales and Use Tax	$17,101,895
Income Tax(withholding on private royalties)	$137,943
Various Ad Valorem and Property Taxes	$902,235
Royalties and Rentals on State Iron Ore	
School Trust Lands	$25,696,263
University Trust Lands	$15,029,345
Tax Forfeit	$1,021,737
Other state accounts	$277,000
Total	**$151,921,418**

Notes for Table 13 above:

All taxes are according to the Department of Revenue's *Minnesota Mining Tax Guide, November 2011* (for 2010 taxes payable in 2011).

Royalties and rentals on state iron ore are from Department of Natural Resources Mineral receipts by Account for Calendar Year 2011. Iron ore and taconite income is 97% of the State's total mineral receipts.

Royalties (2010): $128.4 million in Royalties were paid in 2010 by iron mining industry (Royalties include state and private-owned royalties.)

Occupation taxes: Occupation taxes have increased from $10.3 million in 2007 to $12.6 million in 2010.

Production and other taxes: $97.3 million in Production, Sales and Use, Income and various Ad Valorem Taxes were paid in 2010. These taxes are spread between the General Fund, local units of government and schools. Approximately $17.1 million of this was support to local school districts.

More detail on Minnesota's Iron Mining industry's support for education is shown below. During 2011 (calendar year) Minnesota's Iron Mining industry paid $64.1 million towards Minnesota's education.

Table 14. Minnesota's Iron Mining Industry Support for Education

Source: *MN Depart. Of Revenue, MN DNR*	*School*	*University*	*Total Education*
School district component of Production Tax	$17,094,176		$17,094,176
State iron ore royalties and rent	$25,696,263	$15,029,345	$40,725,608
Occupation Tax	$5,046,800	$1,261,700	$6,308,500
Totals	**$47,837,239**	**$16,291,045**	**$64,128,284**

Notes for Table 14 above:

School district component of Production Tax is according to the Department of Revenue's *Minnesota Mining Tax Guide, November 2011* (for 2010 taxes payable in 2011).

School Trust and University royalties are from Department of Natural Resources Mineral receipts by Account for Calendar Year 2011. Iron ore and taconite income is 97% of the State's total mineral receipts.

Notes (cont.):

Occupation Tax is according to the Department of Revenue's *Minnesota Mining Tax Guide, November 2011*. Total tax is $12,617,000 of which 40% went to elementary and secondary education and 10% went to the University of Minnesota.

Ad Valorem and property tax according to the Department of Revenue's *Minnesota Mining Tax Guide, November 2011*, totaled $902,235, which benefited cities and townships, school districts, counties, and Indian Affairs Council.

The following table, taken from the Department of Natural Resources Mineral Receipts by Account Calendar Years 2010 and 2011, shows royalties and rental receipts to the State as distributed for ferrous mining. Royalties and rental receipts are payments by the mining companies to use the State's non-renewable mineral resources.

Table 15. Minnesota Ferrous Mineral Royalties and Rentals Receipts, 2010 and 2011

Source: *MN DNR, BBER*

Account	***2010 Iron-Ore Taconite***	***2011 Iron-Ore Taconite***
School Trust Fund	$10,487,000	$21,448,000
School Trust Fund (Minerals Mgmt)	$2,071,993	$4,248,263
University Trust Fund	$2,270,000	$12,526,000
University Trust Fund (Minerals Mgmt)	$451,195	$2,503,345
Tax Forfeit	$729,000	$859,000
Tax Forfeit (Minerals Mgmt)	$136,194	$162,737
Advanced Royalty Account	$389,000	$389,000
Totals	**$16,534,382**	**$42,136,345**

Ferrous Mining Development Scenarios

The BBER considered the possibility that only some of the proposed projects will progress to full operations status. The following table presents impact results assuming 75% of Value Added, 75% of Output, and 75% of Employment is achieved by year 2016. The table also shows values for assuming 50% of projects are achieved and for the baseline operations in 2010 (for comparison).

Also, given the variety of projects and the sensitivity of detail surrounding the commercial ventures being proposed, speculation about which projects are most likely to become operational requires treating the subject of ferrous mining development as an aggregated industry of many firms. The following tables present impact results for percentage success rates for expansion and startup projects. Possible 75% and 50% impacts are shown in relation to the baseline data and full implementation scenarios. This calculation is based on decreasing the total hypothetical impacts of value added, output, and employment by 25% and 50%.

75% or 50% Impact:
Possible Ferrous Mining Projects Completed, Minnesota and the Region

Table 16. Ferrous Mining Impact on Minnesota: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$2,752,556,981	$4,331,012,431	14,201
75%	$2,064,417,736	$3,248,259,323	10,651
50%	$1,376,278,491	$2,165,506,216	7,101

Table 17. Ferrous Mining Impact on the Arrowhead Region and Douglas County, Wisconsin: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$2,337,615,098	$3,570,795,747	11,127
75%	$1,753,211,324	$2,678,096,810	8,345
50%	$1,168,807,549	$1,785,397,874	5,564

IV. Findings: Non-Ferrous Mining Impacts

In this section, the BBER reports the direct, indirect, and induced economic impacts of construction and operations activities of non-ferrous mining in Northeast Minnesota, measured in employment, output, and value added. Impacts are modeled for both the State of Minnesota, and the immediate region, including the counties of the Arrowhead Region and Douglas County, Wisconsin.

To provide a baseline reference, the BBER modeled the impact on the State's economy that might be felt if non-ferrous mining and all its transactions had been removed from the State of Minnesota. The BBER uses IMPLAN's most recent data, which is for year 2010, for this impact model. This provides insight to the contribution of the non-ferrous mining industry to the State's economy.

Next, using employment and output projections from the mining industry, as well as assistance from representatives of the State, the BBER modeled the economic impact of proposed new projects in the non-ferrous mining industry sector. A special sub-section of the findings covers the results of modeling non-ferrous mining tax impacts.

Finally, the BBER considered the possibility that not all projects will be viable and will progress to full operations status. Therefore, impacts for two development scenarios are presented to show impact results if only half or only three quarters of projects currently proposed succeed. The 75% and 50% impacts are shown in relation to the baseline data and full implementation scenarios.

Non-Ferrous Mining's Contribution to the State's Economy

IMPLAN provides a model of the economy of the State of Minnesota, including non-ferrous mining (identified as sector 23 copper, nickel, lead, and zinc mining), as presented in the section "Industry Definitions," above. The values in the tables below are estimated from sources associated with the IMPLAN model and also identified above.

In the tables below, the Value Added total measure shows that copper, nickel, lead, and zinc mining contributed more than $157 million in wages, rents, and profits to Minnesota's economy. The Value Added total represents the direct value of the wages, etc., plus the additional inter-industry spending that resulted from these wages, plus any additional household spending that resulted from the direct wages and inter-industry spending.

The Output total measure shows that copper, nickel, lead, and zinc mining produced more than $210 million in local production as part of Minnesota's economy. The Output total represents the direct value of local production, plus the additional inter-industry transactions that resulted from local production, plus any additional household spending that resulted from inter-industry production.

The Employment measure shows that copper, nickel, lead, and zinc mining directly employed almost 200 employees (jobs—including temporary, part-time or short-term) in Minnesota. The Employment total of more than 500 jobs represents the direct employment in the industry sector, plus other jobs dependent on, but not part of, the copper, nickel, lead, and zinc mining sector, plus any jobs created by the additional household spending and activity linked to direct and indirect jobs in the copper, nickel, lead, and zinc mining industry.

The IMPLAN input-output model also provides an opportunity to calculate a multiplier value associated with each of these measures. For example, the employment multiplier for copper, nickel, lead, and zinc mining in the State of Minnesota of 3.1 indicates that for every job in the copper, nickel, lead, and zinc mining industry, another 2.1 jobs are created as the indirect and induced effect of the mining industry's job. In the same way, the model estimates that for every dollar of wages, rents, interest and profits paid to non-ferrous mining employees and companies, another $0.41 is generated through indirect and induced effects throughout the economy of the State.

The impact of mining employment and the payroll associated with these jobs may be the most obvious impact; however the Output measure also shows contribution to the region and to the State through production taxes, royalties, and fees on the exported ore.

Although the total economic impacts for the State are almost always greater than the impacts for the Arrowhead Region and Douglas County, Wisconsin, the importance of mining sector to the region's economy is proportionately greater.

The following tables show the (current operations as of 2010) impact of non-ferrous mining on the State of Minnesota and the region, in 2012 dollars.

Table 18. Minnesota Non-Ferrous Mining Economic Impacts, Baseline 2010

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$111,689,936	$20,769,592	$24,596,460	$157,055,988
Output	$136,398,301	$33,685,684	$40,004,310	$210,088,295
Employment	175	144	232	551

Note direct effects for Value Added, Output, and Employment results in different totals for the State and the region. The regional economy does not enjoy the same level of added indirect and induced effects. This implies, for instance, that copper, nickel, lead, and zinc mining creates about 50 more jobs in the Metro and other parts of the State than the Arrowhead region and Douglas County.

Table 19. Arrowhead and Douglas County, Wisconsin, Non-Ferrous Mining Economic Impacts, Baseline 2010

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$119,445,069	$11,918,069	$23,612,982	$154,976,119
Output	$136,398,301	$19,637,121	$38,794,919	$194,830,341
Employment	175	127	205	507

The top twenty-five Minnesota indirect and induced jobs dependent on copper, nickel, lead, and zinc mining come from the following supporting industries:

Table 20. Non-Ferrous Mining Employment Impacts in Minnesota, Top Twenty-Five Detail, Baseline 2010

Source: IMPLAN

Description	*Direct*	*Indirect*	*Induced*	*Total*
Mining copper, nickel, lead, and zinc	175	0	0	175
Custom computer programming services	0	58	0	58
Food services and drinking places	0	3	24	27
Real estate establishments	0	5	11	16
Private hospitals	0	0	12	12
Offices of physicians, dentists, and other health practitioners	0	0	10	10
Employment services	0	6	4	10
Architectural, engineering, and related services	0	9	1	10
Nursing and residential care facilities	0	0	9	9
Securities, commodity contracts, investments, and related activities	0	3	6	9
Nondepository credit intermediation and related activities	0	2	6	8
Retail Stores - General merchandise	0	0	8	8
Wholesale trade businesses	0	1	7	8
Support activities for other mining	0	8	0	8
Retail Stores - Food and beverage	0	0	7	7
Electric power generation, transmission, and distribution	0	6	1	7
Management of companies and enterprises	0	6	1	7
Civic, social, professional, and similar organizations	0	3	5	8
Monetary authorities and depository credit intermediation activities	0	2	3	5
Services to buildings and dwellings	0	3	3	6
Computer systems design services	0	5	1	6
Individual and family services	0	0	5	5
Retail Nonstores - Direct and electronic sales	0	0	5	5
Legal services	0	3	3	6
Retail Stores - Motor vehicle and parts	0	0	5	5
Total From Top 25	**175**	**123**	**137**	**435**
As well as an additional 116 jobs in various other sectors of the economy	0	21	95	116
Grand Total	**175**	**144**	**232**	**551**

Jobs created as the impact of taxes are included in the model's calculations.

The Economic Impacts of Non-Ferrous Mining Proposed Projects

The BBER modeled the economic impact of proposed expansions and projects in the non-ferrous mining industry sector. Findings from individual projects are aggregated in the tables below and present an estimation of the impact of all currently proposed new start-up projects. The BBER relied on industry representatives and State of Minnesota representatives for its inventory of possible projects. The timeline in Figure 5 shows the BBER's rationale for choosing the year 2016, as the first possible full operations year in which all projects might be operational.

The BBER also modeled the economic impact of the total sector activity, which combines the proposed new projects with the on-going industry in the State. Tables described as "all operations" present the impacts of copper, nickel, lead, and zinc mining in year 2016 as if all new projects were at full operations and are added to the continuing impact of current (2010) copper, nickel, lead, and zinc mining operations.

Minnesota Construction: Proposed Non-Ferrous Mining Projects

Project totals have been aggregated by year. As noted earlier, the time line for project construction is dependent on environmental permitting and the months or years such permitting requires for approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016.

Table 21. Non-Ferrous Mining Construction's Value Added, Output, and Employment Impacts on the State of Minnesota 2012–2016, New Projects, Aggregated

Source: IMPLAN	*Value Added*	*Output*	*Employment*
2012	—	—	—
2013	—	—	—
2014	$157,541,469	$307,592,556	1,020
2015	$157,541,469	$307,592,556	1,020
2016	$560,181,099	$1,093,728,114	2,170

Minnesota Operations: Proposed Non-Ferrous Mining Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all proposed expansions and new projects to be in year 2016.

Table 22. Non-Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the State of Minnesota, New Projects, 2016

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$115,785,590	$21,531,208	$25,498,408	$162,815,205
Output	$141,400,005	$34,920,930	$41,471,260	$217,792,195
Employment	427	352	566	1,345

Minnesota Operations:
All Proposed and Continuing Non-Ferrous Mining, 2016

The table below shows the estimated impact of full operations for all proposed new projects and all continuing industry operations for year 2016.

Table 23. Non-Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the State of Minnesota, 2016, All Operations

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$227,475,526	$42,300,800	$50,094,868	$319,871,193
Output	$277,798,306	$68,606,614	$81,475,570	$427,880,490
Employment	602	496	798	1,896

Region Construction:
Proposed Non-Ferrous Mining Projects

As with the impacts for the State, project totals have been aggregated by year. As noted earlier, the time line for project construction is dependent on environmental permitting and does not forecast the months or years such permitting requires for approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016.

Table 24. Non-Ferrous Mining Construction's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, New Projects, Aggregated, 2012–2016

Source: IMPLAN	*Value Added*	*Output*	*Employment*
2012	—	—	—
2013	—	—	—
2014	$114,596,328	$245,174,222	841
2015	$114,596,324	$245,174,222	841
2016	$407,478,088	$871,782,948	1,790

Region Operations:
Proposed Non-Ferrous Mining Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all new projects to be in year 2016.

Table 25. Non-Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, New Projects, 2016

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$123,825,096	$12,355,096	$24,478,866	$160,659,059
Output	$141,400,005	$20,357,204	$40,217,523	$201,974,731
Employment	427	310	498	1,235

Region Operations:
All Proposed and Continuing Non-Ferrous Mining, 2016

The table below shows the estimated impact of full operations for all proposed new projects and all continuing industry operations, for year 2016.

Table 26. Non-Ferrous Mining Operation's Value Added, Output, and Employment Impacts on the Arrowhead Region and Douglas County, Wisconsin, 2016, All Operations

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$243,270,165	$24,273,165	$48,091,848	$315,635,178
Output	$277,798,306	$39,994,325	$79,012,442	$396,805,072
Employment	602	437	703	1,742

NON-FERROUS TAX IMPACTS

Non-Ferrous Mining Tax Impacts on Minnesota and the Region

In order to estimate non-ferrous tax impacts on Minnesota, the BBER followed the Minnesota DNR's Mineral Receipts by Account for 2010 and 2011. Compared to ferrous mining, non-ferrous mining contributes much less to the State. As displayed in the following table, (again, according to the Department of Natural Resources Mineral Receipts by Account Calendar Year 2010 and 2011) the non-ferrous sector contributed $1,064,871 in 2010 and increased to $1,160,430 in 2011.

Table 27. Minnesota Non-Ferrous Mineral Royalties and Rentals Receipts, 2010 and 2011

Source: *MN DNR, BBER*

Account	*2010 Non-Ferrous Metallic Minerals*	*2011 Non-Ferrous Metallic Minerals*
School Trust Fund	$290,069	$329,353
School Trust Fund (Minerals Mgmt)	$58,014	$65,871
Tax Forfeit	$384,416	$424,535
Tax Forfeit (Minerals Mgmt)	$76,883	$84,907
Consolidated Conservation	$151,203	$112,745
Consolidated Conservation (Minerals Mgmt)	$30,241	$22,549
Volstead Lands	$2,800	$3,400
Volstead Lands (Mineral Mgmt)	$560	$680
Other Land Classes	$61,121	$98,492
Other Land Classes (Mineral Mgmt)	$9,564	$17,898
Totals	**$1,064,871**	**$1,160,430**

Non-ferrous Development Scenarios

The BBER considered the possibility that only some of the proposed projects will progress to full operations status. The following table presents impact results assuming 75% of Value Added, 75% of Output, and 75% of Employment is achieved by year 2016. The table also shows values for assuming 50% of projects are achieved and for the baseline operations in 2010 (for comparison).

Also, given the variety of projects and the sensitivity of detail surrounding the commercial ventures being proposed, speculation about which projects are most likely to become operational requires treating the subject of non-ferrous mining development as an aggregated industry of many firms. The following tables present impact results for percentage success rates for expansion and startup projects. Possible 75% and 50% impacts are shown in relation to baseline data and full implementation scenarios.

75% and 50% Impact:
Possible Non-Ferrous Mining Projects Completed, Minnesota and Region

Table 28. Non-Ferrous Mining Impact on Minnesota: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$162,815,205	$217,792,195	1,345
75%	$122,111,404	$163,344,146	1,009
50%	$81,407,603	$108,896,098	673

Table 29. Non-ferrous Mining Impact on the Arrowhead Region and Douglas County, Wisconsin: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$160,659,059	$201,974,731	1,235
75%	$120,494,294	$151,481,048	926
50%	$80,329,530	$100,987,366	618

V. Findings: Ferrous and Non-Ferrous Mining Impacts

In this section, the BBER reports the direct, indirect, and induced economic impacts of construction and operations activities of both ferrous and non-ferrous mining in Northeast Minnesota, measured in employment, output, and value added. Impacts are modeled for both the State of Minnesota, and the immediate region, including the counties of the Arrowhead Region and Douglas County, Wisconsin.

To provide a baseline reference, the BBER modeled the impact on the State's economy that might be felt if ferrous and non-ferrous mining and all their transactions had been removed completely from the State of Minnesota. This provides insight on the contribution of the ferrous and non-ferrous mining industry to the State's economy. The BBER uses IMPLAN's most recent data, which is for year 2010, for this impact model.

Next, using employment and output projections from the mining industry, as well as assistance from representatives of the State, the BBER modeled the economic impact of proposed expansions and new projects in the ferrous and non-ferrous mining industry sectors. A special sub-section of the findings covers the results of modeling ferrous mining tax impacts.

Finally, the BBER considered the possibility that not all projects will be viable and will progress to full operations status. Therefore, impacts for two development scenarios are presented, to show impact results if only half or only three quarters of projects currently proposed succeed. The 75% and 50% impacts are shown in relation to the baseline data and full implementation scenarios.

Contribution to the State's Economy

IMPLAN provides a model of the economy of the State of Minnesota, including ferrous mining (identified as sector 22 Iron ore mining) and non-ferrous mining (identified as sector 23 copper, nickel, lead, and zinc mining), as presented in the section "Industry Definitions," above. The values in the tables below are estimated from sources associated with the IMPLAN model and also identified above.

In the tables below, the Value Added total measure shows that ferrous and non-ferrous mining contributed almost $2.1 billion in wages, rents, and profits to Minnesota's economy. The Value Added total represents the direct value of the wages, etc., plus the additional inter-industry spending that resulted from these wages, plus any additional household spending that resulted from the direct wages and inter-industry spending.

The Output total measure shows that ferrous and non-ferrous mining produced more than $3.2 billion in local production as part of Minnesota's economy. The Output total represents the direct value of local production, plus the additional inter-industry transactions that resulted from local production, plus any additional household spending that resulted from inter-industry production.

The Employment measure shows that ferrous and non-ferrous mining directly employed more than 4,100 employees (jobs—including temporary, part-time or short-term) in Minnesota. The Employment total of over 11,700 jobs represents the direct employment in the industry sector, plus other jobs dependent on, but not part of, the ferrous and non-ferrous sectors, plus any jobs created by the additional household spending and activity linked to direct and indirect jobs in the Iron ore mining, and copper, nickel, lead, and zinc mining industries.

The IMPLAN input-output model also provides an opportunity to calculate a multiplier value associated with each of these measures. For example, the employment multiplier for ferrous and non-ferrous mining in the State of Minnesota of almost 2.8 indicates that for every job in the ferrous and non-ferrous mining industries, another 1.8 jobs are created as the indirect and induced effect of the mining industries' job. In the same way, the model estimates that for every dollar of wages, rents, interest, and profits paid to mining employees and companies, another $0.66 is generated through indirect and induced effects throughout the economy of the State.

The impact of mining employment and the payroll associated with these jobs may be the most obvious impact; however the Output measure also shows contribution to the region and to the State through production taxes, royalties, and fees on the exported ore and production activity.

Although the total economic impacts for the State are almost always greater than the impacts for the Arrowhead Region and Douglas County, Wisconsin, the importance of the mining sector to the region's economy is proportionately greater.

The following tables show the baseline impact (current operations as of 2010) of ferrous and non-ferrous mining on the State of Minnesota and the region, in 2012 dollars.

Table 30. Minnesota Ferrous and Non-Ferrous Mining Economic Impacts, Baseline 2010

Source: IMPLAN	***Direct Effect***	***Indirect Effect***	***Induced Effect***	***Total Effect***
Value Added	$1,248,522,359	$369,806,013	$459,935,692	$2,078,264,064
Output	$1,848,295,510	$636,625,773	$748,092,928	$3,233,014,212
Employment	4,150	2,417	5,210	11,777

Note direct effects for Value Added, Output, and Employment results in different totals for the State and the region. The regional economy does not enjoy the same level of added indirect and induced effects. This implies, for instance, that ferrous and non-ferrous mining creates about 2,400 more jobs in the Metro and other parts of the State than the Arrowhead region and Douglas County, Wisconsin.

Table 31. Arrowhead and Douglas County, Wisconsin, Ferrous and Non-Ferrous Mining Economic Impacts, Baseline 2010

Source: IMPLAN	***Direct Effect***	***Indirect Effect***	***Induced Effect***	***Total Effect***
Value Added	$1,256,277,492	$242,071,943	$288,216,967	$1,786,566,401
Output	$1,848,295,510	$365,580,736	$473,270,072	$2,687,146,319
Employment	4,150	1,400	3,752	9,302

The Economic Impacts of Proposed Projects

The BBER modeled the economic impact of proposed expansions and projects in the ferrous and non-ferrous mining industry sector. Findings from individual projects are aggregated in the tables below, and present an estimation of the impact of all currently proposed ferrous and non-ferrous mining expansions and new start-up projects. The BBER relied on industry representatives and State of Minnesota representatives for its inventory of possible projects. The time line in Figure 5 shows the BBER's rationale for choosing the year 2016 as the first possible full operations year in which all projects might be operational.

The BBER also modeled the economic impact of the total combined sectors' activity, which combines the proposed expansions and new projects with the on-going industries in the State. Tables described as "all operations" present the impacts of ferrous and non-ferrous mining in year 2016, as if all proposed expansions and new projects were at full operations and are added to the continuing impact of current (2010) mining operations.

Minnesota Construction:
Expansions and Proposed Ferrous and New Non-Ferrous Mining Projects

These projects include investment in facilities improvement and maintenance. The project totals have been aggregated by year. As noted earlier, the time line for project construction is dependent on environmental permitting and the months or years such permitting requires to gain approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016.

Table 32. Ferrous and Non-ferrous Mining Construction's Value Added, Output, and Employment Impacts on the State of Minnesota 2012–2016 (Aggregated, all projects)

Source: IMPLAN	*Value Added*	*Output*	*Employment*
2012	$744,837,822	$1,454,261,964	1,964
2013	$687,678,567	$1,342,661,101	3,079
2014	$295,819,462	$577,574,043	1,607
2015	$317,513,694	$619,921,719	2,278
2016	$661,169,218	$1,290,902,822	3,190

Minnesota Operations:
Expansions and Proposed Ferrous and Non-Ferrous Mining Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all proposed expansions and new projects to be in year 2016.

Table 33. Ferrous and Non-ferrous Mining Expansions and New Projects Operation's Value Added, Output, and Employment Impacts on the State of Minnesota, 2016

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$1,744,550,247	$521,603,368	$649,218,572	$2,915,372,186
Output	$2,594,072,662	$898,766,452	$1,055,965,512	$4,548,804,627
Employment	5,456	3,227	6,863	15,546

Minnesota Operations:
All Ferrous and Non-Ferrous Mining Operations

The table below shows the estimated impact of full operations for all proposed expansions and new projects and all continuing industry operations for year 2016.

Table 34. Minnesota Ferrous and Non-ferrous Mining Economic Impacts: Expansions, Startups, and All Other Operations, Aggregated, 2016

Source: IMPLAN	*Direct Effect*	*Indirect Effect*	*Induced Effect*	*Total Effect*
Value Added	$2,993,072,606	$891,409,381	$1,109,154,264	$4,993,636,250
Output	$4,442,368,172	$1,535,392,225	$1,804,058,440	$7,781,818,839
Employment	9,606	5,644	12,073	27,323

Region Construction:
Expansions and Proposed Ferrous and Non-Ferrous Mining Projects

As with the impacts for the State, these projects include investment in facilities improvement and maintenance. Project totals have been aggregated by year. As noted earlier, the time line for project construction is dependent on environmental permitting and does not forecast the months or years such permitting requires for approval. Construction impacts associated with possible projects are modeled as yearly totals from 2012 to 2016.

Table 35. Ferrous and Non-ferrous Mining Construction's Value Added, Output, and Employment Impacts on the Arrowhead and Douglas County, Wisconsin, 2012–2016 (Aggregated, all projects)

Source: IMPLAN	***Value Added***	***Output***	***Employment***
2012	$541,798,194	$1,159,155,347	1,620
2013	$500,220,297	$1,070,201,130	2,540
2014	$215,180,313	$460,369,606	1,326
2015	$230,937,305	$494,081,067	1,879
2016	$480,937,266	$1,028,945,902	2,631

Region Operations:
Ferrous and Non-Ferrous Expansions and Proposed Projects

Following the assumptions made for the time line of projects, operations impacts assume full production for all proposed expansions and new projects to be in year 2016.

Table 36. Ferrous and Non-Ferrous Mining Expansions and New Projects Operation's Value Added, Output, and Employment Impacts on the Arrowhead and Douglas County, Wisconsin, 2016

Source: IMPLAN	***Direct Effect***	***Indirect Effect***	***Induced Effect***	***Total Effect***
Value Added	$1,752,589,753	$342,101,622	$403,582,781	$2,498,274,157
Output	$2,594,072,662	$515,998,245	$662,699,572	$3,772,770,478
Employment	5,456	1,921	4,985	12,362

Region Operations:
All Ferrous and Non-Ferrous Mining Operations

The table below shows the estimated impact of full operations for all proposed expansions and new projects and all continuing industry operations for year 2016.

Table 37. Arrowhead and Douglas County, Wisconsin, Ferrous and Non-Ferrous Mining Economic Impacts: Expansions, Startups, and All Other Operations, Aggregated, 2016

Source: IMPLAN	***Direct Effect***	***Indirect Effect***	***Induced Effect***	***Total Effect***
Value Added	$3,008,867,245	$584,173,565	$691,799,748	$4,284,840,558
Output	$4,442,368,172	$881,578,981	$1,135,969,644	$6,459,916,797
Employment	9,606	3,321	8,737	21,664

Ferrous and Non-Ferrous Tax impacts

As with the ferrous and the non-ferrous tax impact discussions above, the following tables, taken from the Department of Natural Resources Mineral Receipts by Account Calendar Years 2010 and 2011, show how tax receipts to the State are distributed for both ferrous and non-ferrous mining.

Table 38. Minnesota Ferrous and Non-Ferrous Royalties and Rentals Receipts, 2010 and 2011

Source: *MN DNR, BBER*

Account	*Ferrous Iron-Ore Taconite*	*Non-Ferrous Metallic Minerals*
	2010	
School Trust Fund	$10,487,000	$290,069
School Trust Fund (Minerals Mgmt)	$2,071,993	$58,014
University Trust Fund	$2,270,000	
University Trust Fund (Minerals Mgmt)	$451,195	
Tax Forfeit	$729,000	$384,416
Tax Forfeit (Minerals Mgmt)	$136,194	$76,883
Consolidated Conservation		$151,203
Consolidated Conservation (Minerals Mgmt)		$30,241
Volstead Lands		$2,800
Volstead Lands (Mineral Mgmt)		$560
Other Land Classes		$61,121
Other Land Classes (Mineral Mgmt)		$9,564
Advanced Royalty Account	$389,000	
Totals	**$16,534,382**	**$1,064,871**
	2011	
School Trust Fund	$21,448,000	$329,353
School Trust Fund (Minerals Mgmt)	$4,248,263	$65,871
University Trust Fund	$12,526,000	
University Trust Fund (Minerals Mgmt)	$2,503,345	
Tax Forfeit	$859,000	$424,535
Tax Forfeit (Minerals Mgmt)	$162,737	$84,907
Consolidated Conservation		$112,745
Consolidated Conservation (Minerals Mgmt)		$22,549
Volstead Lands		$3,400
Volstead Lands (Mineral Mgmt)		$680
Other Land Classes		$98,492
Other Land Classes (Mineral Mgmt)		$17,898
Advanced Royalty Account	$389,000	
Totals	**$42,136,345**	**$1,160,430**

Readers are referred to the Appendix A of this report for more on ferrous and non-ferrous tax information. The BBER offers in this appendix sources for ferrous and non-ferrous tax values, more detail on tax impacts and Minnesota's School Trust Lands and Permanent University Funds (PUF), and impact modeling using IMPLAN to estimate Federal, and State and Local taxes. This appendix also shows IMPLAN tax impact comparisons for ferrous and non-ferrous mining in Minnesota and the Arrowhead Region and Douglas County, Wisconsin.

Ferrous and Non-Ferrous Development Scenarios

The BBER considered the possibility that only some of the proposed projects will progress to full operations status. The following table presents impact results assuming 75% of Value Added, 75% of Output, and 75% of Employment is achieved by year 2016. The table also shows values for assuming 50% of projects are achieved.

Also, given the variety of projects and the sensitivity of detail surrounding the commercial ventures being proposed, speculation about which projects are most likely to become operational requires treating the subject of ferrous and non-ferrous mining development as aggregated industries of many firms. The following tables present impact results for percentage success rates for the expansion and startup projects.

75% and 50% Impact:
Possible Ferrous and Non-Ferrous Mining Projects Completed, Minnesota and Region

Table 39. Ferrous and Non-Ferrous Mining Impact on Minnesota: 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$2,915,372,186	$4,548,804,627	15,546
75%	$2,186,529,140	$3,411,603,470	11,660
50%	$1,457,686,093	$2,274,402,314	7,773

Table 40. Ferrous and Non-Ferrous Mining Impact on the Arrowhead Region and Douglas County, Wisconsin, 75% and 50% Impact of Completion of All Proposed Expansions and New Projects

Source: IMPLAN	*Value Added*	*Output*	*Employment*
100%	$2,498,274,157	$3,772,770,478	12,362
75%	$1,873,705,618	$2,829,577,859	9,272
50%	$1,249,137,079	$1,886,385,239	6,181

VII. Conclusions

In the summary tables below, the sector totals increase as the impact moves from the base year (numbers 1 and 2) through the impact of addition of expansions and new projects (numbers 3 through 6), to the hypothetical total (number 7) with includes all impacts.

The IMPLAN model's employment multiplier value associated with impact number 7 below is 2.8. This multiplier estimates that for this grand total impact, for every job in the mining industry, another 1.8 jobs are created as the indirect and induced effect of the mining industry's job. In the same way, for this impact, the model estimates that for every dollar of wages, rents, interest and profits, another $0.67 is generated through indirect and induced effects throughout the economy of the State.

Table 41. Summaries: Ferrous and Non-ferrous Operations Impacts on Minnesota, Baseline 2010, and Proposed Expansions and New Projects, in 2012 Dollars

Source: IMPLAN

			Direct Effect	*Indirect Effect*	*Induced Effect*	*Total Effect*
1)	**2010 Ferrous (Baseline)**	***Value Added***	$1,136,832,423	$349,036,421	$435,339,232	$1,921,208,076
		Output	$1,711,897,209	$602,940,089	$708,088,618	$3,022,925,917
		Employment	3,975	2,273	4,978	11,226
2)	**2010 Non-Ferrous (Baseline)**	***Value Added***	$111,689,936	$20,769,592	$24,596,460	$157,055,988
		Output	$136,398,301	$33,685,684	$40,004,310	$210,088,295
		Employment	175	144	232	551
3)	**Ferrous Expansions and New Projects**	***Value Added***	$1,628,764,657	$500,072,160	$623,720,164	$2,752,556,981
		Output	$2,452,672,657	$863,845,522	$1,014,494,252	$4,331,012,432
		Employment	5,029	2,875	6,297	14,201
4)	**Non-Ferrous New Projects**	***Value Added***	$115,785,590	$21,531,208	$25,498,408	$162,815,205
		Output	$141,400,005	$34,920,930	$41,471,260	$217,792,195
		Employment	427	352	566	1,345
5)	**Total Ferrous (Expansions, New Projects, and 2010 Baseline Operations)**	***Value Added***	$2,765,597,080	$849,108,581	$1,059,059,396	$4,673,765,057
		Output	$4,164,569,866	$1,466,785,611	$1,722,582,870	$7,353,938,349
		Employment	9,004	5,148	11,275	25,427
6)	**Total Non-Ferrous (New Projects and 2010 Baseline Operations)**	***Value Added***	$227,475,526	$42,300,800	$50,094,868	$319,871,193
		Output	$277,798,306	$68,606,614	$81,475,570	$427,880,490
		Employment	602	496	798	1,896
7)	**Total Ferrous and Non-Ferrous (Expansions, New Projects, and 2010 Baseline Operations)**	***Value Added***	$2,993,072,606	$891,409,381	$1,109,154,264	$4,993,636,250
		Output	$4,442,368,172	$1,535,392,225	$1,804,058,440	$7,781,818,839
		Employment	9,606	5,644	12,073	27,323

For the Arrowhead Region and Douglas County, Wisconsin, the IMPLAN input-output model's employment multiplier, for this grand total impact, is 2.3. This multiplier estimates that for every job in the ferrous and non-ferrous mining industries, another 1.3 jobs are created as the indirect and induced effect of the mining industry's job.

In the same way, for this impact, the model estimates that for every dollar of wages, rents, interest, and profits, another $0.42 is generated through indirect and induced effects throughout the economy of the Region.

Table 42. Summaries: Ferrous and Non-ferrous Operations Impacts on the Arrowhead Region and Douglas County, Wisconsin, Baseline 2010, and Proposed Expansions and New Projects, in 2012 Dollars

Source: IMPLAN			***Direct Effect***	***Indirect Effect***	***Induced Effect***	***Total Effect***
1)	**2010 Ferrous (Baseline)**	***Value Added***	$1,136,832,423	$230,153,874	$264,603,985	$1,631,590,282
		Output	$1,711,897,209	$345,943,615	$434,475,153	$2,492,315,978
		Employment	3,975	1,273	3,547	8,795
2)	**2010 Non-Ferrous (Baseline)**	***Value Added***	$119,445,069	$11,918,069	$23,612,982	$154,976,119
		Output	$136,398,301	$19,637,121	$38,794,919	$194,830,341
		Employment	175	127	205	507
3)	**Ferrous Expansions and New Projects**	***Value Added***	$1,628,764,657	$329,746,526	$379,103,915	$2,337,615,098
		Output	$2,452,672,657	$495,641,041	$622,482,049	$3,570,795,747
		Employment	5,029	1,611	4,487	11,127
4)	**Non-Ferrous New Projects**	***Value Added***	$123,825,096	$12,355,096	$24,478,866	$160,659,059
		Output	$141,400,005	$20,357,204	$40,217,523	$201,974,731
		Employment	427	310	498	1,235
5)	**Total Ferrous (Expansions, New**	***Value Added***	$2,765,597,080	$559,900,400	$643,707,900	$3,969,205,380
	Projects, and 2010 Baseline	***Output***	$4,164,569,866	$841,584,656	$1,056,957,202	$6,063,111,725
	Operations)	***Employment***	9,004	2,884	8,034	19,922
6)	**Total Non-Ferrous (New Projects and**	***Value Added***	$243,270,165	$24,273,165	$48,091,848	$315,635,178
	2010 Baseline Operations)	***Output***	$277,798,306	$39,994,325	$79,012,442	$396,805,072
		Employment	602	437	703	1,742
7)	**Total Ferrous and Non-Ferrous**	***Value Added***	$3,008,867,245	$584,173,565	$691,799,748	$4,284,840,558
	(Expansions, New Projects, and 2010	***Output***	$4,442,368,172	$881,578,981	$1,135,969,644	$6,459,916,797
	Baseline Operations)	***Employment***	9,606	3,321	9,122	22,049

Although the total economic impacts for the State are almost always greater than the impacts for the Arrowhead Region and Douglas County, Wisconsin, the importance of mining sector to the region's economy is proportionately greater.

The following graphic representations show comparisons between the 2010 baseline impacts and the hypothetical full operations with additional expansions and new projects. They compare the Value Added, Output, and Employment impacts of Minnesota versus the Arrowhead Region and Douglas County, Wisconsin.

Figure 6. Total Economic Impact of Ferrous and Non-ferrous Mining Payrolls (Value Added) In 2012 Millions of Dollars

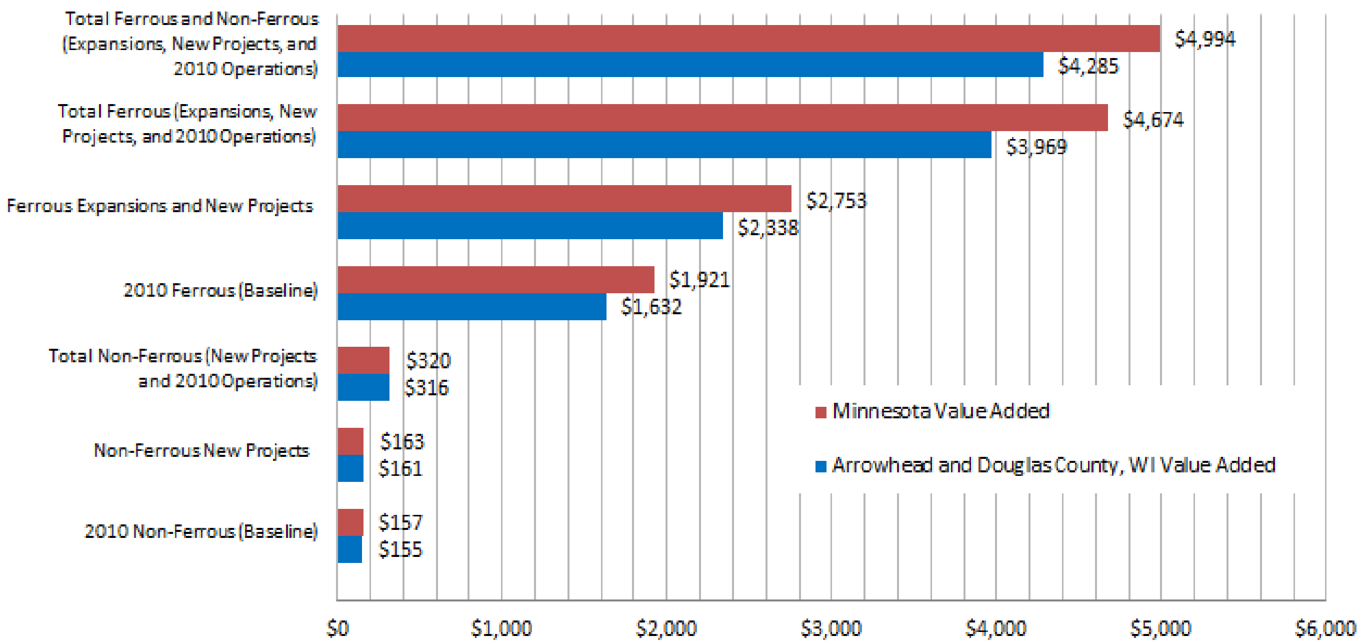


Figure 7. Total Economic Impact of Ferrous and Non-ferrous Mining Production (Output) in 2012 Millions of Dollars

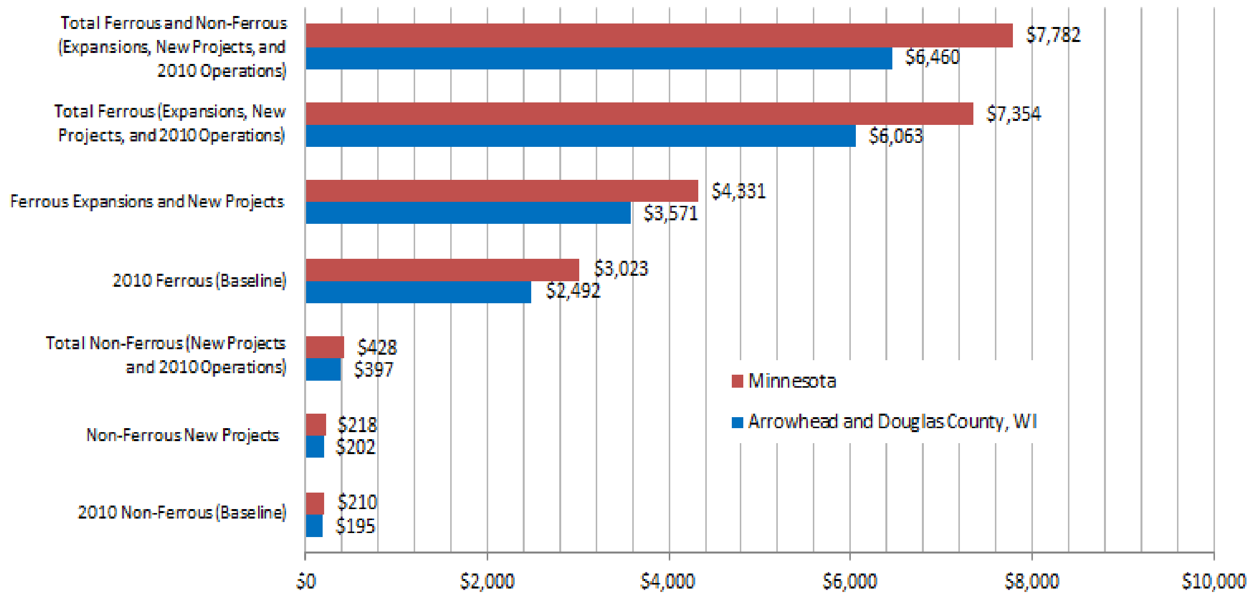
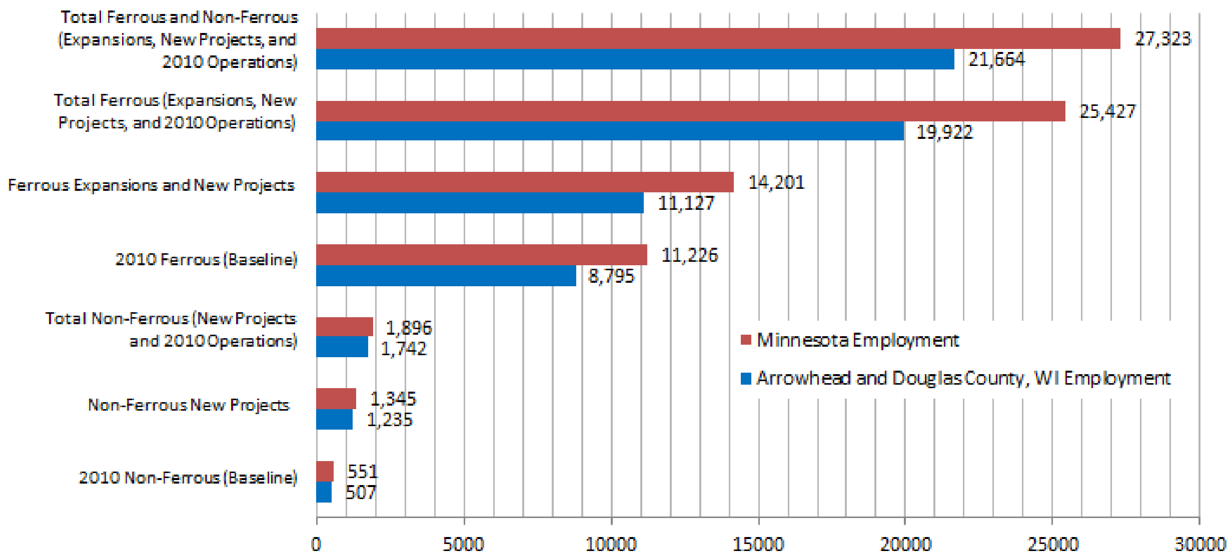


Figure 8. Total Economic Impact of Ferrous and Non-ferrous Mining (Employment)



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Appendix A: Taxes, School Support, and the State of Minnesota's Mineral Revenue

This appendix reproduces secondary data sources for tax impact findings presented in the report, including sources for:

1) Taconite Production Tax

   A severance tax paid on concentrates or pellets produced by the taconite companies. The rate is determined by multiplying the prior year's rate by the percent change in the Gross Domestic Product Implicit Price Deflator from the fourth quarter of the second preceding year to the fourth quarter of the preceding year. The rate for 2010 production was $2.380 per taxable ton. The tax revenue is distributed to various cities, townships, counties, and school districts within taconite mining areas.
2) Occupation Tax

   All mining companies, ferrous or non-ferrous, are subject to the Minnesota Occupation tax. This is similar to a corporate income tax. The tax revenue is credited to the general fund.
3) Sales and Use Tax

   All firms involved in the mining or processing of minerals are subject to the 6.875% sales and use tax on all purchases, except those qualifying for the industrial production exemption.
4) Income Tax (withholding on private royalties)

   All persons or companies paying royalties are required to withhold Minnesota income tax from royalty payments (6.25%) and remit the withholding tax and applicable information to the Minnesota Department of Revenue.
5) School district component of production tax
6) Various Ad Valorem and property taxes

   Lands that include un-mined taconite and iron ore are subject to the ad valorem and property taxes. Lands and structures actively used for taconite production are exempt from the ad valorem tax and are subject to the production tax instead of the property tax.

This appendix also includes background information on,

7) Minnesota's School Trust Lands, and Permanent University Funds (PUF)

Finally, this appendix includes a tax impact study from the IMPLAN model for purposes of comparison.

8) IMPLAN model tax impact comparisons for ferrous and non-ferrous mining in Minnesota and the Arrowhead Region and Douglas County, Wisconsin.

1) Taconite Production Tax

Figure 9. Taconite Production Tax

Source: Minnesota Mining Tax Guide, November 2011, pg. 16.

Taconite Production Tax Distribution*

Production year	2005	2006	2007	2008	2009	2010
City and township	$2,047,900	$2,091,131	$2,053,321	$2,087,203	$1,741,289	1,707,978
Township Fund	–	–	–	1,161,019	961,848	938,421
Taconite municipal aid	6,454,084	6,588,041	6,484,790	6,568,276	5,361,555	5,234,627
M.S. 298.28, Subd 3(b)***	–	–	–	–	49,156	93,382
Mining effects	1,769,593	1,806,224	1,773,075	1,802,316	1,503,108	1,474,603
School district — regular	1,512,883	1,567,083	1,553,181	1,579,632	1,329,597	1,296,216
School district fund	5,928,663	6,134,022	5,932,765	6,939,441	5,823,744	5,670,746
School Building Maintenance Fund	–	–	–	1,548,025	1,256,439	1,217,160
Taconite Levy Shortfall Payment	–	–	–	–	501,635	807,218
Taconite Referendum Fund	4,218,742	3,985,816	3,636,432	3,324,393	3,067,031	2,974,743
County	9,984,746	10,112,692	9,934,767	8,904,372	8,861,655	8,862,567
County road and bridge	2,637,217	2,671,467	2,623,622	4,527,635	3,760,396	3,657,961
Taconite Property Tax Relief	13,719,754	33,269	10,635,240	9,656,986	3,435,404	11,846,794
IRRRB ($.03 Indexed)	3,071,150	3,289,341	3,327,352	3,472,124	2,881,831	2,811,548
Range Association of Municipalities and Schools	104,092	137,886	136,469	139,165	113,697	110,294
Taconite railroad (fixed)	2,482,454	2,482,454	2,482,454	2,482,454	2,482,454	2,482,454
IRRRB (fixed)	1,252,520	1,252,520	1,252,520	1,252,520	1,252,520	1,252,520
School bond payments	4,767,129	3,747,420	4,265,993	4,360,743	4,119,962	4,021,158
Taconite Environmental Protection Fund	9,417,968	11,537,116	11,003,226	10,280,483	13,200,509	6,386,643
Producer Grant & Loan Fund	3,098,810	3,177,818	3,157,554	3,196,114	2,831,630	2,782,967
Douglas J. Johnson Economic Protection Trust Fund	2,864,404	4,001,532	3,682,303	3,197,366	4,302,341	842,910
IRRRB Educational Revenue Bonds	–	1,415,106	1,411,525	1,410,125	1,407,525	1,408,725
Iron Range Higher Education Acct	–	–	1,896,471	1,935,031	1,570,547	1,521,884
Biomass Energy Project Loan	–	–	3,882,294	–	–	–
Renewable Energy Initiative	–	–	–	5,998,597	–	–
Taconite Economic Development Fund	11,520,660	12,257,357	8,503,411	12,213,126	254,341	9,673,605
Hockey Hall of Fame	–	76,669	75,860	77,401	62,822	60,876
Transfer from schools to cities**	–	11,444	157,095	30,239	0	–
Public Works & Local Economic Development Fund	–	14,720,531	4,323,954	–	9,032,845	–
Total	**$86,852,769**	**$93,096,939**	**$94,185,674**	**$98,144,786**	**$81,165,881**	**$79,138,000**

* The production tax is collected and distributed in the year following production. For example, the 2010 production tax was collected and distributed during 2011.
** This is excess school levy reduction money that will be used to reduce levies of cities and townships within the school district.
***Prior to 2009, this amount was included in the Taconite municipal aid amounts.

2) Occupation Tax

Figure 10. Occupation Tax Paid by Company

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 34

Occupation Tax Paid by Company

	2003 (000's)	2004 (000's)	2005 (000's)	2006 (000's)	2007 (000's)	2008 (000's)	2009 (000's)	2010 (000's)
Hibbing Tac	$7	$1,141	$1,525	$2,175	$2,260	$5,420	$0	$300
Arcelor-Mittal	35	124	240	130	680	1,137	0	0
National Steel*	0	0	0	0	0	0	0	0
Northshore	0	41	25	280	832	1,563	340	707
United Tac	0	354	770	151	1,086	2,600	0	2,010
USS - Minntac	1,400	3,104	4,000**	5,000**	5,500**	12,668**	0	9,600
USS - Keetac	0	147						
Taconite total	**$1,442**	**$4,911**	**$6,560**	**$7,736**	**$10,358**	**$23,388**	**$340**	**$12,617**
Mesabi Nugget	$-	$-	$-	$-	$-	$-	$-	$0
Direct-reduced iron (DRI) total	$-	$-	$-	$-	$-	$-	$-	**$0**
Magnetation	$-	$-	$-	$-	$-	$-	$-	$0
Natural ore total	$-	$-	$-	$-	$-	$-	$-	**$0**
Total tax paid	**$1,442**	**$4,911**	**$6,560**	**$7,736**	**$10,358**	**$23,388**	**$340**	**$12,617**

*The former National Steel is now USS-Keewatin Taconite (Keetac).
** USS-Minntac & USS-Keetac file a combined return.

3) Sales and Use Tax

Figure 11. Use Tax Paid

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 43

Use Tax Paid

Year	Use tax	Refund claims*	Net use tax collected
2000	18,829,904	12,698,510	6,131,394
2001	14,123,142	15,775,844	(1,652,702)
2002	13,694,774	12,850,487	844,287
2003	12,435,693	11,238,116	1,197,577
2004	17,139,316	8,624,502	8,514,814
2005	20,219,218	12,393,334	7,825,884
2006	23,191,259	14,446,391	8,744,868
2007	25,795,536	19,191,938	6,603,598
2008	24,225,373	14,670,700	9,554,673
2009	16,040,963	18,876,729	(2,835,766)
2010	$25,303,605	$8,201,710	$17,101,895

* These are capital equipment refund claims allowed, not including interest, for new or expanding businesses and for repair and replacement parts.

4) Income Tax (withholding on private royalties)

Figure 12. Royalty Paid and Income Tax Withheld

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 40

Royalty Paid and Income Tax Withheld
(Taconite, natural ore and others)

Year	Royalty paid	Income tax withheld
2001	$45,448,947	$265,587
2002	$37,903,733	$142,422
2003	$45,173,508	$216,629
2004	$56,726,329	$214,962
2005	$77,298,269	$332,015
2006	$86,238,285	$238,142
2007	$87,154,748	$334,975
2008	$118,761,439	$415,491
2009	$62,952,973	$207,365
2010	$128,435,093	$137,943

5) School district component of production tax

Figure 13. Taconite Production Tax Distributions to School Districts, 2011

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 19

Taconite Production Tax Distributions to School Districts - 2011

School districts		$.0343 Taconite School Fund	$.1572 Regular School Fund	Taconite Railroad	$.04 School Bldg Maintenance Fund	$.213 Taconite Referendum	Tax. Levy Replacement Shortfall Paymt*	Total
001	Aitkin	–	$144,173	–	–	$0	$14,589	$158,762
166	Cook County	$21,087	34,328	$264,977	–	0	0	320,392
182	Crosby-Ironton	–	164,510	–	–	0	15,649	180,159
316	Greenway	33,373	528,737	–	$87,511	256,312	65,102	971,035
318	Grand Rapids	–	630,768	–	–	261,840	43,237	935,845
319	Nashwauk-Keewatin	90,994	178,845	–	40,784	112,834	65,678	489,135
381	Lake Superior	71,496	284,579	342,720	73,637	116,056	38,188	926,676
695	Chisholm	–	484,006	–	53,116	206,397	69,014	812,533
696	Ely	–	55,256	–	–	57,293	14,340	126,889
701	Hibbing	210,360	950,706	–	152,875	563,724	252,503	2,130,168
706	Virginia	74,908	575,814	–	171,976	313,585	94,444	1,230,727
712	Mtn. Iron-Buhl	371,682	333,784	–	76,870	199,470	53,526	1,035,332
2142	St. Louis County	147,484	346,560	284,841	220,786	225,644	32,740	1,258,055
2154	Eveleth-Gilbert	91,495	598,086	–	218,515	326,119	48,208	1,282,423
2711	Mesabi East	183,337	360,594	214,397	121,090	335,469	0	1,214,887
Totals		$1,296,216	$5,670,746	$1,106,935	$1,217,160	$2,974,743	$807,218	$13,073,018

*Made from Taconite Property Tax Relief Account

Figure 14. Taconite Production Tax School Bond Payments

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 19

Taconite Production Tax School Bond Payments

School districts		Year authorized[1]	Final payment year[2]	Payment[3]	Outstanding balance[4]
166	Cook County[5]	1996	2016	$503,465	$2,684,500
316	Greenway	2000	2019	154,516	1,120,000
318	Grand Rapids	1996	2010	475,730	0
381	Lake Superior	2000	2022	391,821	3,574,112
695	Chisholm	2000	2020	297,738	2,462,717
696	Ely	1996	2015	68,686	300,000
701	Hibbing	1996	2011	212,512	204,000
706	Virginia	1996	2016	795,904	2,161,076
712	Mt. Iron-Buhl	1998	2017	325,308	1,900,000
2154	Eveleth-Gilbert	1996	2017	234,916	1,976,000
2711	Mesabi East	1996	2011	60,562	60,000
2711	Mesabi East	2008	2016	500,000	0
Totals:				$4,021,158	$16,442,405

1 Legislative year in which taconite funding was enacted.
2 Production year from which final bond payment will be deducted.
3 Payments made from 2010 pay 2011 tax distribution
4 Estimated portion of outstanding bond balance to be paid by taconite funds (not including interest).
5 All taconite bonds funded at 80 percent taconite, 20 percent local effort, unless otherwise noted: Cook County – 1996, 70 percent
Mesabi East – 2008, $500,000

6) Various ad Valorem and property taxes

Figure 15. Iron Ore Ad Valorem Tax Payable

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 49

Iron Ore Ad Valorem Tax Payable

Year assessed	Market value	Payable	Year estimated tax payable			Total
			Crow Wing	Itasca	St. Louis	
1996	4,448,800	1997	10,900	34,900	226,200	272,000
1997	4,175,400	1998	10,400	23,500	244,900	278,800
1998	4,020,900	1999	8,200	18,900	188,100	215,200
1999	3,781,800	2000	4,200	20,200	181,800	206,200
2000	3,765,800	2001	3,900	18,600	159,400	181,900
2001	3,637,400	2002	3,500	17,600	147,200	168,300
2002	2,720,400	2003	3,500	16,900	107,200	127,600
2003	2,734,200	2004	3,300	15,400	101,600	120,300
2004	2,529,200	2005	2,700	14,100	87,300	104,100
2005	2,355,700	2006	2,700	13,300	77,400	93,400
2006	2,350,100	2007	2,500	12,700	79,100	94,300
2007	2,255,300	2008	2,300	11,600	68,400	82,300
2008	2,345,800	2009	2,200	11,400	70,100	83,700
2009	2,347,000	2010	2,200	12,200	71,500	85,900
2010	2,345,500	2011	2,400	12,700	76,400	91,500
2011	2,341,600	2012				

Figure 16. Taconite Railroad Ad Valorem Tax Assessed

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 50

Taconite Railroad Ad Valorem Tax Assessed					
Year payable	Assessed	St. Louis County	Lake County	Cook County	Total tax
1995	1994	$78,281	$140,300	$14,454	$233,034
1996	1995	64,516	116,143	14,456	195,115
1997	1996	49,283	61,107	13,292	123,682
1998	1997	46,250	66,114	10,330	122,694
1999	1998	43,891	68,874	8,648	121,413
2000	1999	42,340	65,444	8,542	116,326
2001	2000	35,467	64,295	8,500	108,262
2002	2001	27,323	37,336	7,202	71,861
2003	2002	6,746	17,890	0	24,636
2004	2003	4,519	15,964	0	20,483
2005	2004	3,896	13,312	0	17,208
2006	2005	3,366	10,921	0	14,287
2007	2006	3,054	10,081	0	13,135
2008	2007	3,212	9,063	0	12,275
2009	2008	2,562	6,415	0	8,977
2010	2009	2,319	7,293	0	9,612
2011	2010	2,514	7,223	0	10,137

Figure 17. Tax Collection and Distribution

Source, Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg.51

Tax Collection and Distribution			
Period ending	80% retained by local government	20% payment to Indian Business Loan Account	Total collections of affected counties
Dec. 31, 2002	707,716	176,929	884,645
Dec. 31, 2003	461,456	115,364	576,820
Dec. 31, 2004	342,468	85,617	428,085
Dec. 31, 2005	542,524	135,631	678,155
Dec. 31, 2006	341,884	85,471	427,355
Dec. 31, 2007	451,904	112,976	564,880
Dec. 31, 2008	433,578	108,395	541,973
Dec. 31, 2009	463,472	115,868	579,340
Dec. 31, 2010	448,864	112,216	561,080

Figure 18. Unmined Taconite Tax Paid

Source: Minnesota Mining Tax Guide, Minnesota Department of Revenue, November 2011, pg. 47

Unmined Taconite Tax Paid

(Year payable)

County	2004	2005	2006	2007	2008	2009	2010	2011
Itasca	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
St. Louis	300,173	273,601	261,687	532,102	495,033	466,991	238,274	239,518
Totals	**$300,173**	**$273,601**	**$261,687**	**$532,102**	**$495,033**	**$466,991**	**$238,274**	**$239,518**

7) Permanent University Funds (PUF)

The Minnesota Department of Natural Resources (DNR) administers more than 12 million acres of state-owned mineral rights. As of January 2012, there are 25,845 total acres of permanent university fund lands, with an additional 21,368 acres of mineral rights. The minerals management account was designed to create a $3 million principal that could be drawn upon in the event that future income generation drops. The $3 million level was reached in Fiscal Year 2007. At the end of each fiscal year the amount exceeding $3 million is distributed to the Permanent School Fund and Permanent University Fund in proportion to the revenue contributed to the minerals management account by these two land types. For Fiscal Year 2011, the Permanent University Fund will receive $1,285,875 transfer from the minerals management account.

Figure 19. FY 2011 Proceeds to be Transferred to the PUF

Source: Minnesota's Permanent University Land and Fund, Minnesota DNR, February 2012, pg. 5

Mineral lease revenue to DNR's Permanent University Account	$10,023,146.60
Transfer from minerals management account	1,285,875.26
Forest, Suspense Account, Land Sale, and real estate lease revenue to DNR's Permanent University Account	$111,338.10
TOTAL transferred to Permanent University Fund	**$11,420,359.96**

Figure 20. FY 1992-2011 Mineral Lease Revenue Distribution by Account

Source: Minnesota's Permanent University Land and Fund, Minnesota DNR, February 2012, pg. 6

(Note: Revenue earned in a FY is transferred to the PUF in the following FY)

FY	Endowed Mineral Research Account	Endowed Scholarship Account	Total
1992	$1,485,903.50	$1,485,903.50	$2,971,807.00
1993	$2,003,975.50	$2,003,975.50	$4,007,951.00
1994	$1,931,548.50	$1,931,548.50	$3,863,097.00
1995	$2,636,377.00	$2,636,377.00	$5,272,754.00
1996	$2,712,847.14	$2,712,847.14	$5,425,694.28
1997 *	$1,217,628.85	$1,217,628.85	$2,435,257.70
1998	$806,960.06	$806,960.06	$1,613,920.12
1999	$673,229.62	$673,229.62	$1,346,459.23
2000	$416,364.08	$416,364.08	$832,728.15
2001	$1,020,555.16	$1,020,555.16	$2,041,110.31
2002 **	$930,779.53	$930,779.53	$1,861,559.06
2003	$2,759,933.17	$2,759,933.17	$5,519,866.33
2004	$2,342,521.57	$2,342,521.57	$4,685,043.14
2005	$3,774,828.09	$3,774,828.09	$7,549,656.17
2006***	$2,835,833.00	$2,835,833.00	$5,671,666.00
2007****	$4,513,724.83	$4,513,724.83	$9,027,449.66
2008****	$4,494,636.83	$4,494,636.83	$8,989,273.67
2009****	$3,962,402.33	$3,962,402.33	$7,924,804.67
2010****	$914,090.50	$914,090.50	$1,828,181.00
2011****	$5,654,510.93	$5,654,510.93	$11,309,021.86
TOTAL	**$47,088,650.19**	**$47,088,650.19**	**$94,177,300.35**

* The 1997 data does not include the $250,000 one-time appropriation from the university lands and minerals suspense account.

** The 2002 data does not include a $459,525.91 administration and management fee under Minnesota Statutes, §93.223, subd. 2.

*** The 2006 data does not include the $1,417,795 transferred to the minerals management account.

**** The 2007 data does not include the $1,593,561 transferred <u>to</u> the minerals management account, but does include the $1,059,644 transferred <u>from</u> the minerals management account. The 2008 data does not include the $1,876,064 transferred to the minerals management account, but does include the $1,485,017 transferred from the minerals management account. The 2009 data does not include the $1,684,862 transferred to the minerals management account, but does include the $638,827 transferred from the minerals management account. The 2010 data does not include the $451,195 transferred to the minerals management account, but does include the $9.417 transferred from the minerals management account. The 2011 data does not include the $2,503,345 transferred to the minerals management account, but does include the $1,285,875 transferred from the minerals management account.

The Endowed Scholarship Account, which started receiving revenue from mining of permanent university fund lands in Fiscal Year 1993, has resulted in the University of Minnesota's largest endowed scholarship program. The first scholarships were awarded in Fiscal Year 1994. Now over 20% of the University of Minnesota's new freshmen who are Minnesota residents receive an Iron Range Scholarship.

Figure 21. FY 1994-2011 Distribution of Endowed Scholarship Account Income*

Source: Minnesota's Permanent University Land and Fund, Minnesota DNR, February 2012, pg. 7

FY**	UM - Twin Cities	UM – Duluth	UM – Morris	UM – Crookston	TOTAL
1994	$58,635.00	$19,517.00	$4,922.00	$1,782.00	$84,856.00
1995	$116,080.00	$38,637.00	$9,743.00	$3,528.00	$167,988.00
1996	$232,573.00	$79,341.00	$21,112.00	$7,491.00	$340,517.00
1997	$323,094.00	$111,072.00	$29,820.00	$11,173.00	$475,159.00
1998	$458,013.00	$158,751.00	$41,883.00	$16,888.00	$675,535.00
1999	$572,418.00	$198,404.00	$51,501.00	$21,951.00	$844,274.00
2000	$715,901.00	$247,050.00	$60,879.00	$27,333.00	$1,051,163.00
2001	$853,500.28	$293,515.94	$71,125.02	$32,056.35	$1,250,197.59
2002	$895,541.15	$308,186.23	$75,045.35	$34,020.56	$1,312,793.29
2003	$824,531.76	$284,183.28	$69,044.53	$31,020.01	$1,208,779.58
2004	$789,287.74	$272,099.19	$66,024.07	$30,010.94	$1,157,421.94
2005	$832,139.00	$286,734.00	$69,548.00	$31,724.00	$1,220,145.00
2006	$886,643.51	$305,515.01	$74,103.64	$33,801.67	$1,300,063.83
2007	$951,555.92	$327,882.11	$79,528.88	$36,276.35	$1,395,243.26
2008	$1,234,792.00	$425,478.00	$103,201.00	$47,074.00	$1,810,545.00
2009	$1,424,235.00	$554,765.00	$90,128.00	$51,532.00	$2,120,660.00
2010	$1,550,235.85	$603,844.09	$98,101.58	$56,091.02	$2,308,272.54
2011	$1,562,866.30	$608,763.89	$98,900.87	$56,548.02	$2,327,079.08
TOTALS	$14,282,042.51	$5,123,738.74	$1,114,610.94	$530,300.92	$21,050,693.11

* FY 1993 revenues totaling $18,832 were returned to the principal.

** Amounts provided for FYs 1994 – 2000, 2008, and 2009 were rounded. Amounts for FYs 2001- 2007, 2010 and 2011 are not subject to rounding.

Distribution of Collected Royalties:

Figure 22. Mineral Revenue (in thousands) FY 2002-2011

Source: Revenue Received from State Mineral Leases, Minnesota DNR, April 2012, pg. 8

FY	School Trust Lands	University Trust Lands	Tax-Forfeited Lands and Minerals	Other Land Classes	Special Advance Royalties	Total Revenue
2002	$4,669	$2,321	$554	$25	$13	$7,582
2003	$6,705	$5,453	$616	$26	$299	$13,099
2004	$5,616(*)	$4,685(*)	$328	$25	$275	$628
2005	$11,565	$7,550	$1,493	$62	$322	$20,992
2006	$11,160	$7,089	$1,302	$77	$346	$19,974
2007	$16,549	$9,960	$1,611	$93	$320	$28,533
2008	$20,972	$9,380	$539	$108	$389	$31,388
2009	$16,792	$8,268	$760	$128	$324	$26,272
2010	$10,487	$2,270	$729	$252	$389	$14,127
2011	$21,448	$12,526	$859	$277	$389	$35,499
Total	$120,347	$64,817	$8,791	$1,073	$3,065	$198,094

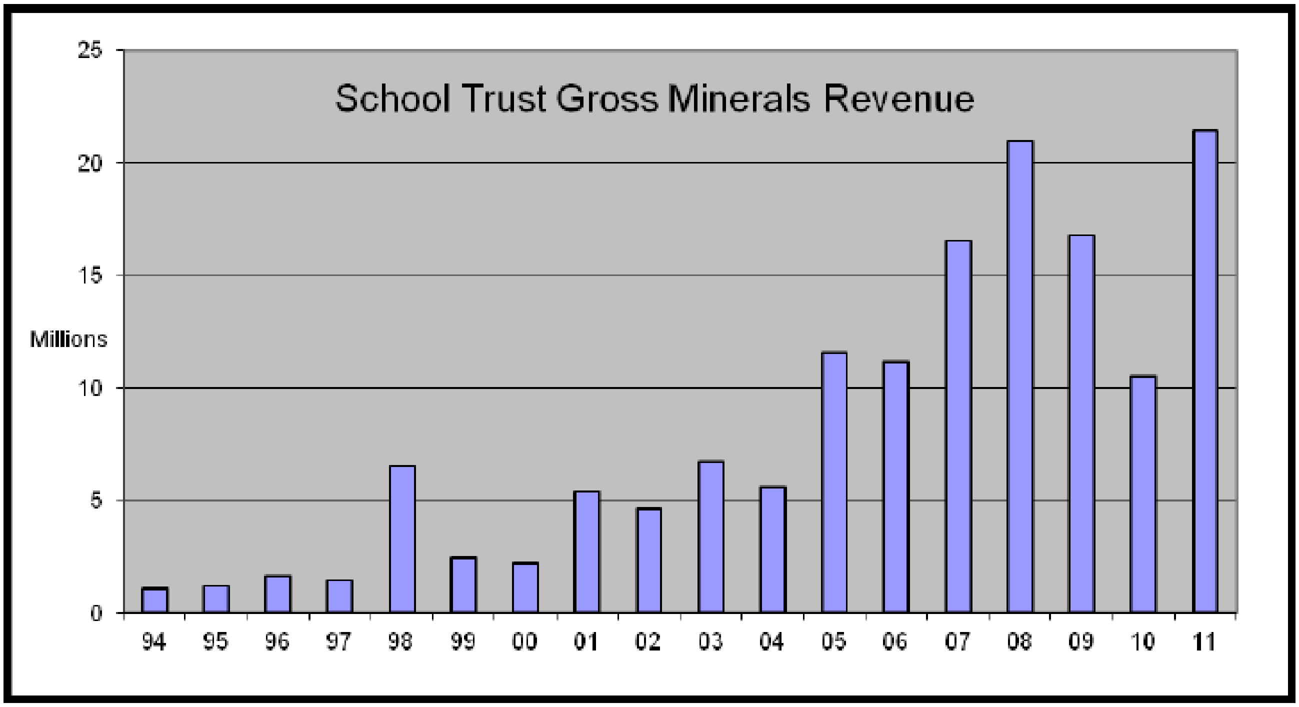
Figure 23. Revenue from Mineral Leases, FY 2010-2011

Source: Minnesota's School Trust Lands, Minnesota DNR, March 2012, pg. 9

	FY10	FY11
Taconite and Iron ore rents/royalties	$10,101,699	$20,921,168
Non-ferrous metallic minerals	$290,069	$329,436
Stockpiling/Surface leases	$4,320	$4,320
Peat	$77,319	$137,601
M-leases	$13,752	$42,481
Industrial Minerals	$0	$13,102
Total	**$10,487,159**	**$21,448,108**

Figure 24. School Trust Fund Gross Minerals Revenue FY 1994-2011

Source: Minnesota's School Trust Lands, Minnesota DNR, March 2012, pg. 10



8) IMPLAN tax modeling

Source: IMPLAN, BBER

The following tax impact values are based on the existing relationships of the data found in the IMPLAN database. The general sources for that data include National Income and Product Accounts (NIPA) from the Bureau of Economic Analysis (BEA); the Bureau of the Census's annual Consumer Expenditure Survey (CES), and the Bureau's Annual Survey of State and Local Government Finances, as well as the BEA's Regional Economic Information System (REIS).

IMPLAN tracks tax impacts through "Employee Compensation, Proprietary Income, Household Expenditure, Enterprises (Corporations), and Indirect Business Taxes." Federal tax impacts include "Corporate Profits Tax, Indirect Bus Tax: Custom Duty, Indirect Bus Tax: Excise Taxes, Indirect Bus Tax: Fed NonTaxes, Personal Tax: Estate and Gift Tax, Personal Tax: Income Tax, Personal Tax: NonTaxes (Fines- Fees, Social Ins Tax- Employee Contribution, and Social Ins Tax- Employer Contribution."

According to the IMPLAN model, state tax impacts include "Corporate Profits Tax, Dividends, Indirect Bus Tax: Motor Vehicle Lic, Indirect Bus Tax: Other Taxes, Indirect Bus Tax: Property Tax, Indirect Bus Tax: S/L NonTaxes, Indirect Bus Tax: Sales Tax, Indirect Bus Tax: Severance Tax, Personal Tax: Estate and Gift Tax, Personal Tax: Income Tax, Personal Tax: Motor Vehicle License, Personal Tax: NonTaxes (Fines- Fees, Personal Tax: Other Tax (Fish/Hunt), Personal Tax: Property Taxes, Social Ins Tax- Employee Contribution, and Social Ins Tax- Employer Contribution."

Readers are cautioned that comparisons with the foregoing Minnesota Department of Revenue and Minnesota Department of Natural Resources tax accounting do not compare easily with results from the IMPLAN model. However, the ability of IMPLAN to model tax impacts is demonstrated in the following comparisons for ferrous and non-ferrous mining in Minnesota and the Arrowhead Region and Douglas County, Wisconsin.

The IMPLAN tax impact is presented below for Federal and State totals.

Table 43. Ferrous Mining Tax Impact on Minnesota, 2016

Source: IMPLAN	*Employee Compensation*	*Proprietor Income*	*Indirect Business Tax*	*Households*	*Corporations*	*Total*
Federal Govt, NonDefense	$106,270,736	$6,643,855	$11,659,937	$67,672,704	$62,733,588	$254,980,820
State/Local Govt, NonEducation	$1,894,478	$0	$65,727,414	$33,751,865	$10,315,824	$111,689,581
	$108,165,214	$6,643,855	$77,387,351	$101,424,569	$73,049,412	$366,670,401

This table shows state and local taxes of almost $111.7 million. This amount includes taxes that are not directly attributable to production.

The totals compile the direct, indirect, and induced effects of business and household spending. With the exception of indirect business taxes and sales and use taxes, these are additional taxes paid by business and workers to state and local government.

Table 44. Tax Impact Totals, Including Proposed Expansions and New Projects as Well as On-Going Ferrous and Non-Ferrous Operations, 2016

Source: IMPLAN, BBER	*Minnesota*	*Arrowhead and Douglas County, Wisconsin*
Iron ore mining:		
Federal Government NonDefense	$254,980,820	$215,651,408
State/Local Govt NonEducation	$111,689,581	$97,895,406
Totals	**$366,670,401**	**$313,546,814**
Copper, nickel, lead, and zinc mining:		
Federal Government NonDefense	$31,583,140	$31,869,803
State/Local Govt NonEducation	$28,792,696	$23,690,264
Totals	**$60,375,836**	**$55,560,067**
Ferrous and Non-Ferrous mining:		
Federal Government NonDefense	$286,563,960	$247,521,211
State/Local Govt NonEducation	$140,482,277	$121,585,669
Totals	**$427,046,237**	**$369,106,880**

Appendix B: Additional Information

Readers are encouraged to remember the BBER is providing an economic impact analysis. Policy recommendations should be based on the "big picture" of total impact, and a cost-benefit analysis would be needed to assess the environmental, social, and governmental impacts of ferrous and non-ferrous mining in the State.

Although a detailed cost-benefit analysis is beyond the scope of this report, a few points currently surrounding ferrous and non-ferrous mining activity in Minnesota and the Arrowhead and Douglas Counties are provided below.

1) Employment trends

Employment data show the continuing importance of the mining sector.

Table 45. Minnesota Mining Employment and Payroll

Source: MN DEED Census of Employment and Wages (CEW)

Year	*Average Number of Employees*	*Annual Wages*
2002	5517	$273,016,618
2003	5139	$279,122,837
2004	5219	$295,623,992
2005	5132	$311,659,581
2006	5147	$335,058,894
2007	5222	$342,880,476
2008	5510	$394,811,584
2009	4419	$281,094,812
2010	5223	$384,668,356
2011	5811	$474,225,320

As a measurement of how important mining is to the Arrowhead Region, mining employment in the Region can be compared to the State. Location quotients identify the significance of an economic sector to the economic base of the state or region. When location quotients are sorted, those above 1.0 are usually considered part of the economy's base, and therefore, exporting industries. Those less than 1.0 are supporting industries, and thus, net importers. When sorted for importance, the mining sector in the Arrowhead Region leads all other sectors, showing mining activity in the Region to be at least ten times more important than any other sector in the economy compared to the State.

Table 46. Location Quotients, Arrowhead Region, Compared to the State of Minnesota, 2011

Source: IMPLAN

	Arrowhead	***MN***	***Location Quotient***
Total, All Industries	137,866	2,604,196	
Mining	339	19,191	10.10
Utilities	3,107	5,811	1.99
Public Administration	5,586	98,601	1.60
Arts, Entertainment, and Recreation	8,611	300,904	1.41
Accommodation and Food Services	1,490	14,177	1.27
Health Care and Social Assistance	2,961	126,093	1.26
Retail Trade	17,443	280,750	1.17
Construction	3,206	93,222	1.07
Other Services (except Public Administration)	398	57,199	0.98
Educational Services	4,591	136,378	0.82
Transportation and Warehousing	1,087	35,879	0.65
Finance and Insurance	3,333	128,850	0.64
Administrative and Support and Waste Management and Remediation Services	854	72,683	0.58
Real Estate and Rental and Leasing	4,032	130,774	0.57
Manufacturing	9,389	215,983	0.54
Professional, Scientific, and Technical Services	28,297	425,713	0.49
Wholesale Trade	3,630	48,621	0.44
Agriculture, Forestry, Fishing and Hunting	13,962	207,111	0.33
Management of Companies and Enterprises	4,359	84,240	0.22
Information	10,254	121,418	0.13

2) Direct and indirect benefits from the mining industry to the State of Minnesota.

One way to examine the indirect and induced impacts from direct jobs in mining in St. Louis County, for example, is to show other jobs in the economy of the Region and of the State that are dependent on mining but not necessarily situated in the mining venues. This list implies occupations in industries supplying mining workers with transportation, eating and drinking establishments, healthcare providers, housing, and infrastructure, for the county, the region, and the State. In the report itself, a discussion is offered for comparing indirect and induced jobs in the region and the state, and thereby demonstrating the jobs supporting mining are outside the region but in the State.

Table 47. Indirect and Induced Jobs Dependent on Iron Ore Mining Employment in Minnesota, 2010

Source: IMPLAN

Industry	***Direct***	***Indirect***	***Induced***	***Total***
Mining iron ore	3,975	20	0	3,995
Food services and drinking places	0	37	519	556
Transport by truck	0	342	35	377
Real estate establishments	0	31	237	268
Wholesale trade businesses	0	125	141	266
Private hospitals	0	0	247	247
Electric power generation, transmission, and distribution	0	208	17	225
Offices of physicians, dentists, and other health practitioners	0	0	224	224
Nursing and residential care facilities	0	0	201	201
Nondepository credit intermediation and related activities	0	63	133	196
Retail Stores - General merchandise	0	8	172	180
Support activities for other mining	0	171	0	171
Retail Stores - Food and beverage	0	8	159	167
Management of companies and enterprises	0	140	26	166
Securities, commodity contracts, investments, and related activities	0	25	137	162
Employment services	0	57	88	145
Civic, social, professional, and similar organizations	0	18	109	127
Mining and quarrying sand, gravel, clay, and ceramic and refractory minerals	0	116	0	116
Individual and family services	0	0	107	107
Retail Stores - Motor vehicle and parts	0	8	97	105
Retail Nonstores - Direct and electronic sales	0	4	100	104
Monetary authorities and depository credit intermediation activities	0	28	73	101
Services to buildings and dwellings	0	36	56	92
Retail Stores - Miscellaneous	0	4	83	87
Architectural, engineering, and related services	0	67	17	84
Total From Top 25	**3,975**	**1,516**	**2,978**	**8,469**
As well as an additional 2,757 jobs in another 279 various sectors of the economy…	0	757	2,000	2,757
Grand Total	**3,975**	**2,273**	**4,978**	**11,226**

THE PERILS OF EFFICIENCY: AN ANALYSIS OF AN UNEXPECTED CLOSURE OF THE POE LOCK AND ITS IMPACT

October 2015

NATIONAL PROTECTION AND PROGRAMS DIRECTORATE

OFFICE OF CYBER AND INFRASTRUCTURE ANALYSIS

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EXECUTIVE SUMMARY

One of the Nation's most economically vital systems, the iron mining - integrated steel production - manufacturing supply chain is potentially one of the least resilient to disruption. The Poe Lock at the Soo Locks connecting Lakes Huron and Superior is a potential single point of failure in this supply chain. An unexpected 6-month closure of the locks would have devastating consequences for industries dependent on this supply chain, particularly the automobile manufacturing industry, and the National economy.

The iron ore extracted from mines located in Minnesota and Michigan is used by steel mills along the Great Lakes to make steel for the appliance, automobile, construction, farm, and mining equipment manufacturers, railcar production and other industries. These steel mills make various grades of steel to supply different markets and different categories within markets. Almost every steel mill makes some type of steel for the automotive industry, the market that dominates the steel industry.

The iron ore shipped from Lake Superior to the Great Lakes steel mills transits the Soo Locks, a set of locks owned and operated by the United States Army Corps of Engineers (USACE). An unanticipated closure of the Poe Lock, the only lock large enough at the Soo Locks to allow passage of the Lake Carriers carrying iron ore, would be catastrophic for the Nation. Depending on what time of year the closure occurred, approximately 75 percent of the U.S. integrated steel production would cease within 2–6 weeks after the closure of the Poe Lock. Approximately 80 percent of iron ore mining operations, and nearly 100 percent of the North American appliances, automobile, construction equipment, farm equipment, mining equipment, and railcar production would shut down. The shutdowns in production of these products would begin slowly and then increase quickly as the stress grows in the iron mining – integrated steel production – manufacturing supply chains. Almost 11 million people in the United States and potentially millions more in Canada and Mexico would become unemployed due to the production stoppage, and the economy would enter a severe recession. There are no plans or solutions that could mitigate the damage to the manufacturing industries dependent on this supply chain.

This report, developed by the Office of Cyber and Infrastructure Analysis' (OCIA) National Infrastructure Simulation and Analysis Center (NISAC) describes the iron mining – integrated steel production – manufacturing supply chain and its history and presents analysis of the impacts of an unanticipated closure and the challenges facing various potential mitigation strategies. OCIA stresses that there is no plan for closing the Soo Locks and no specific reason to believe that the Soo Locks would close. The intent of this report is to highlight the dependency of the North American economy on this set of locks, particularly the Poe Lock. The Poe Lock has been called the Achilles' heel of the Great Lakes navigation system, though it more aptly may be described as the Achilles' heel of the North American industrial economy. The report concludes with some potential mitigation strategies for further analysis, but no single strategy is sufficient to mitigate the disruption.

KEY FINDINGS

- **One the Nation's most economically vital systems, the iron mining - integrated steel production - manufacturing supply chain, is also potentially the least resilient.**
- **A disruption of the Poe Lock likely will cause an almost complete shutdown of Great Lakes steel production.**
- **A shutdown of Great Lakes steel production likely will cause almost all North American appliances, automobile, construction equipment, farm equipment, mining equipment, and railcar production to cease within weeks.**
- **The disruption would likely result in widespread bankruptcies and dislocations throughout the economy. Almost 11 million people would likely be unemployed because of the impact and the North American economies would likely enter a severe recession.**

CONTENTS

FIGURES

TABLES

BACKGROUND

MINES TO PORTS

FIGURE 1—IRON ORE MINES AND PORTS

One the Nation's most economically vital systems, the iron mining—integrated steel production—manufacturing supply chain, is also potentially one of the least resilient. [1,2,3] The iron ore, extracted from mines located primarily in Minnesota (see Figure 1), and to a lesser extent in Michigan, is used by steel mills, generally located along the Great Lakes (see Appendix A for a listing of the iron ore mines; see Figure 2 for a map of the Great Lakes). The three largest steel mills, which account for about half of the domestic integrated steel capacity, are located at the southern tip of Lake Michigan, around Gary, Indiana: Indiana Harbor (ArcelorMittal), Gary Works (U.S. Steel), and Burns Harbor (ArcelorMittal). Appendix B provides a complete list of U.S. steel mills.

[1] While the term 'iron ore' is used throughout the paper, technically the product is taconite. The iron ore mined in the Mesabi Range, MN was depleted during World War II; during the extraction of the iron ore, the taconite, which was considered a waste product, was discarded. Later, a process was developed to crush the taconite and to use a magnet to extract the iron ore.

[2] The terms 'steel' and 'integrated steel' are used interchangeably throughout this report, but refer to the same type of steel.

[3] Iron ore, which is the primary focus of this report, is the predominant commodity transiting the Soo Locks. Coal, which is the second largest commodity, is discussed in the Lightering Section and in Appendix E. Grains, which is the third largest commodity group transported through the Soo Locks, is the only commodity primarily destined for the export market.

FIGURE 2—THE GREAT LAKES

Iron ore pellets are extremely heavy and the mines use specialized railroad cars, called iron ore jennies, which are less than one-half the size of a standard railcar, to move the iron ore from the mines to the iron ore ports (see Figure 1 and Table 1).[4] Each of the iron ore jennies carries about 85 net or short tons of iron ore the average 70 miles from the mines to the iron ore docks.[5]

TABLE 1—IRON ORE DOCKS[6]

Dock Name	Location	Owner	Storage Capacity (tons)	Load Speed (tons per hour)	Rail Served
Hallet Dock #5	Duluth, MN	Hallet Dock Company	800,000	N/A	BNSF, CN
DMIR Dock #6	Duluth, MN	CN Railway	3,000,000	10,000	CN
CN Ore Dock	Escanaba, Michigan	CN Railway	2,000,000	4,000	CN
Northshore Mining	Silver Bay, Minnesota	Cliffs Natural Resources	3,000,000	6,000	CN
BNSF Dock #5	Superior, Wisconsin	BNSF Railroad	3,500,000	6,000	BNSF
Two Harbors	Two Harbors, Minnesota	CN Railway	2,500,000	10,000	CN
Presque Isle	Marquette, Michigan	CN Railway	57,000	3,500	CN

Most of the iron ore extracted in Minnesota and Michigan must be processed, prior to use, in pelletizing plants located near the iron ore mines. The iron ore must go through a beneficiation process of crushing and grinding to separate and remove waste material. The iron ore may then be mixed with limestone (which is shipped east to west through the Soo Locks) and other chemicals to make iron ore pellets.[7,8] There are many different grades and

[4] Taconite has a density of about 2800 kilograms/cubic meters, which is more than double the density of coal (1350 kilograms/cubic meters) and more than triple the density of grains (2800 kilograms/cubic meters) two other products commonly transported by vessel and rail (see SI Metric at http://www.simetric.co.uk/si_materials.htm, accessed May 10, 2015).
[5] Different industries within this supply chain use different definitions of what constitutes a ton. To simplify the analysis, long tons and metric tons were converted into short tons or net tons, which are the same.
[6] The data for this table comes from two sources, the USACE Navigation Data Center (http://www.navigationdatacenter.us/ports/ports.htm) and Greenwood's Guide to Great Lakes Shipping 2015 (Harbor House Publishers: Boynce City, Michigan).
[7] Technically, the limestone is calcite or dolomite. The calcite is lower in magnesium and the mills mix calcite and dolomite to get a specific percentage of magnesium. Calcite is more commonly shipped to the iron ore mines for pelletizing.

sizes of iron ore pellets and they are not interchangeable. Since the early twentieth century, chemists would take samples of iron ore from railcars that were *en route* from mines to iron ore docks and telegraph or telephone the chemical make-up to the facilities at the docks, so that comparable grades of iron ore could be combined for shipment to a particular steel mill.[9] The use of a different pellet could affect steel quality and the blast furnace lining.[10] This process continues today and iron ore pellets, which are about 63 percent iron ore, are shipped by freighter through the Soo Locks.[11]

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[8] When extracted, the taconite may have an iron ore content of 30 percent. The taconite is crushed and ground at taconite processing plants, which are located either at the mines, between the mines and the ports, or at the ports. The taconite must be ground to a fine size so that the iron ore can be extracted by magnetic separate or flotation resulting in production of an iron concentrate. This iron ore concentrate is pelletized into what is called a standard (or acid) pellet or a flux pellet. Both acid and flux pellets have iron content of approximately 65 percent, with flux pellets containing approximately 10 percent limestone or dolomite. The pellets are sized according to the specs of the particular blast furnace to which they will be shipped.

[9] Joachim, George J., "Iron Fleet: The Great Lakes in World War II," Wayne State University Press: Detroit, 1994.

[10] A blast furnace converts the iron ore pellets into liquid iron called 'hot metal' that goes to the basic oxygen furnace to be made into a steel slab (see American Steel and Iron Institute, "The Basic Oxygen Steelmaking Process" at https://www.steel.org/Making%20Steel/How%20Its%20Made/Processes/Processes%20Info/The%20Basic%20Oxygen%20Steelmaking%20Process.aspx?siteLocation=88e232e1-d52b-4048-9b8a-f687fbd5cdcb, accessed April 29, 12015.

[11] U.S. Environmental Protection Agency, "Taconite Ore Processing," at http://www.epa.gov/ttnchie1/ap42/ch11/final/c11s23.pdf, accessed February 5, 2015, and Minnesota Department of Natural Resources, "Taconite," http://www.dnr.state.mn.us/education/geology/digging/taconite.html, accessed February 5, 2015. An alternative method still used as some facilities is called sintering. Sintering takes fine grains of purified low-grade ore into larger shapes with the source of the ore coming from a region outside of Lake Superior. (see Rogers, Robert P., "An Economic History of the American Steel Industry," Routledge Exploration in Economic History).

PORTS TO MILLS

FIGURE 3—PORTS TO STEEL MILLS

There are 13 integrated steel mills in North America. About 50 percent of the iron ore used by the integrated steel mills is shipped directly from the iron ore docks to the mills through the Poe Lock at the Soo Locks. All of the steel mills in Indiana and Michigan, and Lake Erie Works (U.S. Steel) in Ontario receive their iron ore by this pathway (see Figure 3). Another 20 percent of the iron ore used by the integrated steel mills is shipped through the Soo Locks to a Lake Erie port for trans-shipment to a steel mill. In the case of Cleveland East and West (ArcelorMittal), the trans-shipment is onto a smaller vessel that can transit the Cuyahoga River. In the other cases, the trans-shipment is by rail to the final destination. The remaining steel mills either receive their iron ore directly from Minnesota by rail or from sources that do not require shipping through the Poe Lock.

Turning the iron ore pellets into steel is a two-stage process. In the first stage, the pellets are melted into liquid iron in a blast furnace, using oxygen, coking coal, natural gas, and other chemicals while ensuring the proper balance of silicon, sulfur, manganese, and phosphorus. The liquid iron is poured into a basic oxygen furnace along with some scrap steel; oxygen is injected into the mix at supersonic speeds to burn away excess carbon and other impurities. Limestone is then added to gather the impurities into a 'slag' that is discarded. The liquid steel is sent to a treatment facility where the final chemistry and quality is achieved prior to being sent to a caster facility or slab casting area to be processed into a slab. Slabs, which can weigh up to 40 tons, can be 2–7 feet wide, 32 feet long, and up to 1 foot thick (see Figure 4). Slabs can be stored outdoors for specific customers, and, when needed, rolled in the hot rolling and cold rolling facilities to be made into a steel coil (see Figure 4).

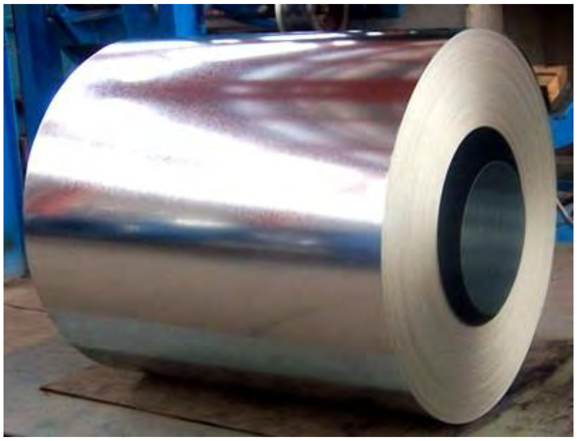

FIGURE 4—STEEL SLAB AND COIL[12]

TYPES OF STEEL PRODUCED IN NORTH AMERICA

In this report, steel refers to steel made in a basic oxygen furnace (BOF), which converts iron ore into steel. BOF steel plants have historically been referred to as integrated steel mills and were the large steel mills located between Illinois and Pennsylvania. Most steel today—about 60 percent of the approximately 120 million ton domestic capacity—is made in an electric arc furnace (EAF), and more commonly referred to as a 'mini-mill'. Mini-mills convert scrap steel into steel using electricity. As their names suggest, mini-mills are typically far smaller than the traditional integrated steel mills. They generally produce steel for specific markets or geographic areas. EAF mills generally have lower cost structures associated with non-union labor, lack of legacy pension plans, and geographic flexibility.

BOF steel has the properties of 'high strength', 'low weight', and 'formability', which means that the steel can be pressed to a thin layer and formed to meet certain shapes and strengths, such as those for an automobile body or frame. EAF steel is used for its strength, particularly in the construction field, as structural steel or rebar. BOF steel and EAF steel are not interchangeable. As one industry expert said, "Mini-Mills are not an option either.[13] They do not produce many of the types of steel that the auto industry requires such as Advanced High Strength Steels or expose quality sheet for outer vehicle panels. Their material could be used for perhaps 50 percent or 60 percent of the components used to build a vehicle. But a vehicle cannot be produced with 60 percent of the parts, it needs every single component." Another industry expert maintained that mini-mills could only supply about 15 percent of the necessary steel, while others said that they cannot use any products coming out of mini-mills. The amount of steel that could be supplied by mini-mills varies by auto manufacturer, but in no case can a car be manufactured using just EAF steel. One of the main drivers for the use of Advanced High Strength steels is the Corporate Average Fuel Economy (CAFE) standards that mandate increasingly high fuel economy for new cars. A car made just from EAF steel would weigh far more than a car made from BOF steel and would not meet the CAFE standards.

[12] Wikipedia, "Semi-finished casting products" at http://upload.wikimedia.org/wikipedia/commons/d/df/Slabs_stack.jpg, accessed May 10, 2015.
[13] Much of the information obtained for this report came from people associated with the broader supply chain. Everyone we spoke with provided very candid and open assessments, for which we are extremely grateful, and we agreed that we would not disclose any identifying information. Any reference to "industry executive" in this report covers these frank discussions.

FIGURE 5—COKE BATTERY SHOWING THE SIDE-BY-SIDE OVENS AND A RAILROAD CAR OF INCANDESCENT COKE[14]

Coking coal is one of the ingredients that helps convert the iron ore pellets into liquid iron. Coking coal is made in coke batteries that concentrate the carbon from coal to make an almost pure form of carbon. Coking coal is also referred to as 'coke' or 'metallurgical coal'.[15] Coking coal is an essential ingredient in steelmaking while thermal coal is used in electric power generators to produce electricity.[16] The coke battery is a series of high-temperature ovens stacked in a row, as shown in Figure 5. These ovens heat coal to 1,100°C in an oxygen-deficient atmosphere to produce coke with low impurities and high-energy content.

[14] American Iron and Steel Institute, "Steelworks: the Online Resource for Steel" Web page "Coke Production for Blast Furnace Ironmaking,"2015, at www.steel.org/Making%20Steel/How%20Its%20Made/Processes/Processes%20Info/Coke%20Production%20For%20Blast%20Furnace%20Ironmaking.aspx, accessed May 18, 2015.
[15] For more information about the process, see World Coal Association, "Coal and Steel," at http://www.worldcoal.org/coal/uses-of-coal/coal-steel/, accessed April 27, 2015.
[16] Ibid.

VESSEL TRANSPORTATION

ONE THOUSAND FOOTERS AND OTHER LAKERS

FIGURE 6—THE LAKER "EDWIN H. GOTT"[17]

Iron ore is moved from mines to one of six ports on Lake Superior or one small port on Lake Michigan. Most of the iron ore is loaded onto one of 13 Class X bulk freight Lake Carriers, more commonly known as 'One Thousand Footers', or 'Footers' (see Figure 6). [18] The One Thousand Footers are about the length of four 747 aircraft nose to tail. They each carry approximately 70,000 tons of iron ore, which is about the equivalent of seven trains with 100 rail cars each or about 3,000 trucks.[19,20] Another 35 vessels carry iron ore, coal, grain, limestone and other products on the Great Lakes and those vessels, together with the One Thousand Footers, are commonly called 'Lakers.' The smaller Lakers that carry iron ore generally do so for specialized trade. For instance, a One Thousand Footer cannot unload iron ore at the Cleveland steel mill; rather a One Thousand Footer unloads iron ore at the Cleveland Bulk Terminal and the iron ore is placed onto smaller Lakers that can transit the Cuyahoga River. The Rouge River in Detroit poses a similar challenge.

The Lakers are self-unloading vessels that require no on-shore equipment to unload iron ore. A Laker can dock at a steel mill and unload their cargo in about 10–12 hours with a crew of about 20 people. While iron ore ports worldwide unload vessels at the rate of about 3,000 tons per hour, the Great Lakes Lakers can unload at rates of up to 10,000 tons per hour. The Great Lakes fleet remains almost the only fleet that uses self-unloading technology.[21] For more information about the Great Lakes fleet, see Appendix C.

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17 From the private collection of Dr. Craig S. Gordon.
18 USACE designates a Class based on the length of the vessel. Class X refers to vessels from 950 to 1,099 feet. For a complete description, see Appendix C.
19 The term 'Lakers' may also refer to other classes of Lake Freighters, both American and Canadian, that are smaller, but still carry bulk commodities. Some of these smaller vessels can transit from Lake Superior to the Atlantic Ocean. The vessels that do enter the Atlantic Ocean are referred to as 'Salties.'
20 The 70,000-ton figure is an approximation depending on water levels in the Great Lakes and the current depth of the Poe Lock. The design capacity of the vessels may be closer to 80,000 tons if St. Marys River was dredged deeper and the Poe Lock had a deeper lakebed elevation.
21 Thompson, Mark L. "Steamboats & Sailors of the Great Lakes," Wayne State University Press: Detroit, 1991.

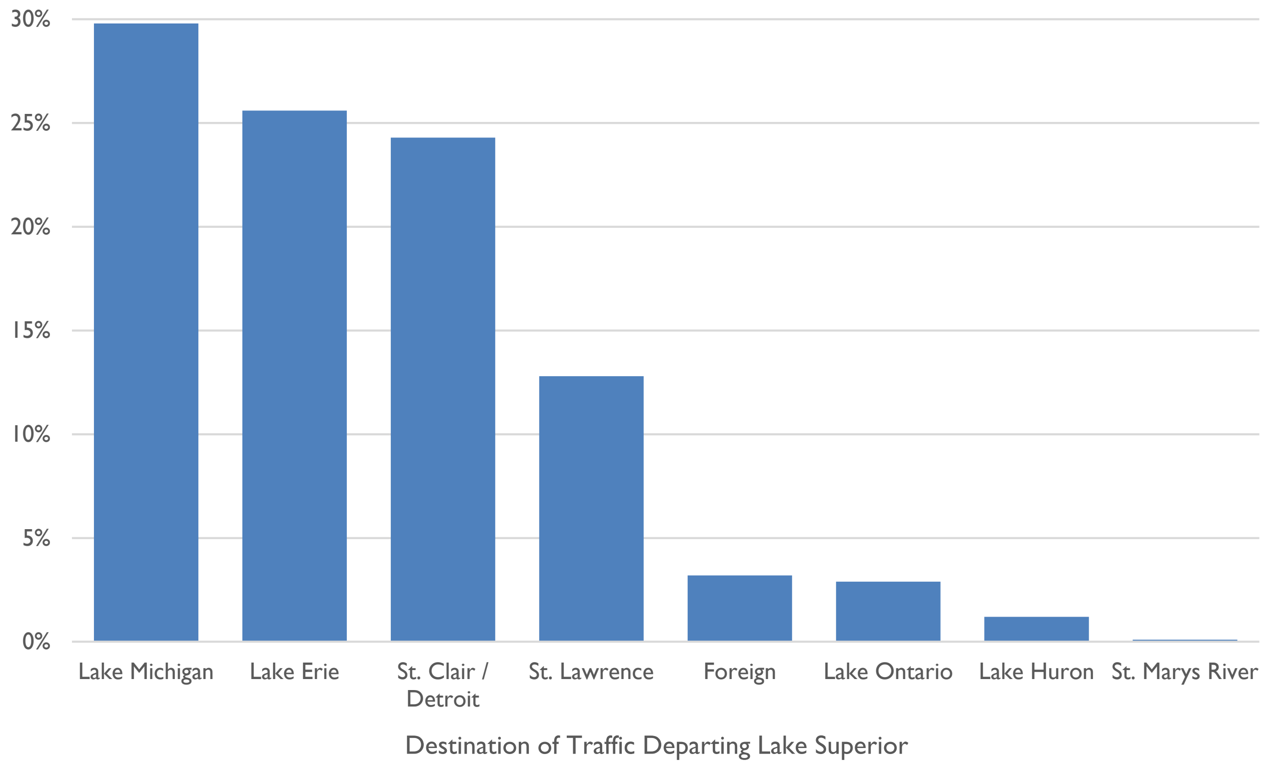

FIGURE 7—EASTBOUND TRAFFIC FROM LAKE SUPERIOR THROUGH THE SOO LOCKS[22]

Figure 7 shows the termination point for all commodities that originates in Lake Superior. About 30 percent of the traffic goes from Lake Superior to Lake Michigan and over 25 percent of the traffic goes from Lake Superior to Lake Erie. Both of these routes are likely only iron ore, while the traffic to St. Clair and Detroit is likely a mix of coal and iron ore. Wheat and oilseed dominate the remaining locations for Lake Superior-originating traffic; much of this moves on Canadian-flagged Lakers. The westbound trade into Lake Superior is about one-ninth of the eastbound trade; limestone dominates the westbound traffic.

[22] USACE, "Statistical Report of Lake Commerce Passing through St. Marys Falls Canal, Sault Ste. Marie, Michigan During the 2013 Navigation Season." Copies from 2004-2012 were also accessed.

SOO LOCKS

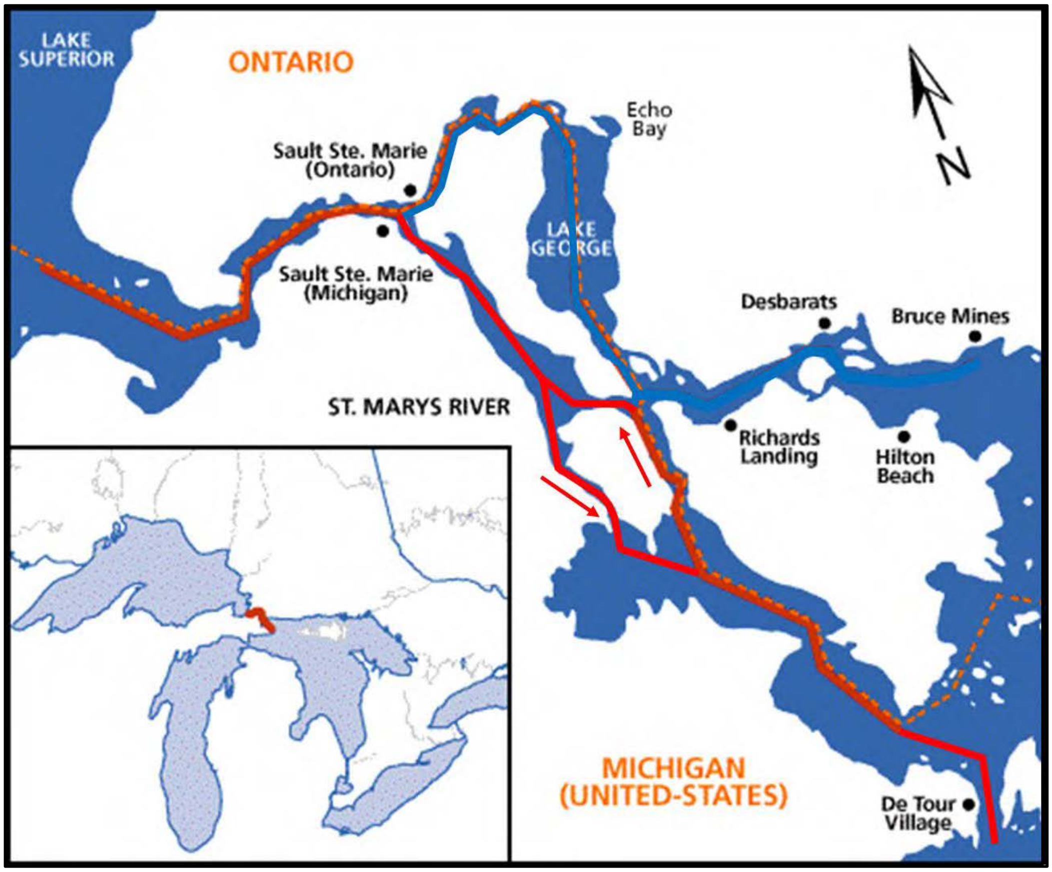

FIGURE 8—ST. MARYS RIVER[23]

From Lake Superior, the iron ore moves to Lake Huron through St. Marys River (see Figure 8), a 63-mile long narrow stretch that defines the Michigan-Canada border.[24] The St. Marys River has been described as not so much a river as a series of lake-connected canals.[25] Between Sault Ste. Marie, Ontario and Sault Ste. Marie, MI, the river drops 21 feet in a three-quarter-mile stretch.[26] To manage the rapids, a group of locks were created, now known as the Soo Locks.[27] Once the Lakers transit St. Marys River, about 43.5 million tons of iron ore are delivered to steel mills located around Gary, IN or Detroit, or to Ohio ports in Ashtabula, Cleveland, Conneaut, and Toledo, a portion of which is transported by rail to steel mills in Pennsylvania, Ohio, and Kentucky. [28,29,30]

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23 Adapted from the Canadian Heritage Rivers System Web page, "St. Marys River" 2011, at www.chrs.ca/Rivers/StMarys/StMarys-M_e.php, accessed May 18, 2015.
24 Lake Superior is so named not because it is the largest of the Great Lakes, but because it is the highest.
25 Bowlus, W. Bruce, "Iron Ore Transport on the Great Lakes," McFarland: Freemont, OH, 2009.
26 USACE, "Soo Locks History," at www.lre.usace.army.mil/Missions/Recreation/SooLocksVisitorCenter/SooLocksHistory.aspx, accessed January 2, 2015.
27 The names of the Soo Locks, Sault Ste. Marie, MI and Sault Ste. Marie, Ontario derive from the rapids; Sault is the old French word for rapids and Soo is an anglicized derivation of Sault.
28 USACE, "Statistical Report of Lake Commerce Passing through St. Marys Falls Canal, Sault Ste. Marie, Michigan During the 2013 Navigation Season." Copies from 2004-2012 were also accessed.
29 After removing the anomalous year of 2009.
30 Two smaller steel mills, Granite City Works (U.S. Steel) in Granite City, IL and Fairfield Works (U.S. Steel) in Fairfield, AL receive iron ore directly by rail from Minnesota.

FIGURE 9—THE FOUR LOCKS OF THE SOO LOCKS

The Soo Locks, which are owned and operated by the United States Army Corps of Engineers (USACE), consists of four locks (see Figure 9).[31] The two primary locks in operation are the Poe Lock, rebuilt in 1968, and the MacArthur Lock, constructed in 1943.[32] The Lakers carrying iron ore use the Poe Lock almost exclusively because the MacArthur Lock is too small to accommodate the larger Lakers; almost 70 percent of the U.S. Laker capacity on the Great Lakes is Poe-restricted, meaning that the Lakers can use only the Poe Lock.[33] Lakers small enough to lock through the MacArthur Lock are referred, herein, as MacArthur-sized. The dependency on the Poe Locks to move the preponderance of the commodities, particularly iron ore, led USACE to call the Poe Lock "the Achilles' heel of the Great Lakes Navigation System. There is currently no redundancy for the Poe Lock."[34] This lock is the weak link in Great Lakes commerce.[35] The Sabin Lock closed in 1989 and the Davis Lock has not been used since 2008. Both of these locks are about 100 years old and are too shallow to permit the transit of bulk carriers. USACE has installed a cofferdam on either side of the Sabin Lock, which sealed the lock in preparation for the permanent dewatering of the lock and the construction of a new lock.[36,37]

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31 The locks operate as follows. When a vessel enters the locks to "lock down" from the Lake Superior side, the gate on the Lake Huron side of the lock remains closed and the Lake Superior gate closes. A valve on the Lake Huron side opens and water flows out until the water level in the lock is the same as that of Lake Huron. Then, the gate on the Lake Huron side opens and the vessel moves out. The gate on the Lake Huron side then closes. A vessel coming from Lake Huron goes through a similar process; in this case, the valve on the Lake Superior side opens to allow water to enter until the water level is the same as the Lake Superior side.

32 The original lock was built by the Northwest Fur Company in 1797, and was destroyed during the War of 1812. Because of the increase in iron ore mining needed for the Midwest steel mills, Congress provided a 750,000 acre land grant to the State of Michigan for the purpose of raising funds to build the State Lock which opened in 1855 (see Bowlus, W. Bruce, "Iron Ore Transport on the Great Lakes," McF: Fremont, OH, 2010). As the iron ore trade increased, a new lock was needed, which opened in 1881. The original lock was closed a few years later, when it was widened and re-opened as the Poe Lock in 1896. The Poe Lock locks through about 70 percent of the tonnage that transits the Soo Locks.

33 According to 33 CFR (Code of Federal Regulations) 207.440, the maximum overall dimensions of vessels that will be permitted to transit MacArthur Lock are 730 feet in length and 75 feet in width. However, whenever the Poe Lock is out of service for a period exceeding 24 hours the District Engineer may allow vessels greater than 730 feet in length, but not exceeding 767 feet in length to navigate the MacArthur Lock.

34 USACE, "Great Lakes Navigation System: Economic Strength to the Nation," on January 2009 at www.lre.usace.army.mil/Portals/69/docs/Navigation/GLN_Strength%20to%20the%20Nation%20Booklet2013v2_final2w.pdf, accessed February 23, 2015.

35 USACE/Great Lakes and Ohio River Division, "Supplemental Reconnaissance Report."

36 A cofferdam is a temporary structure built within or across a dam or lock that allows the lock or dam to be dewatered.

37 There is a plan to remove the Sabin and Davis Locks and build a new Poe-sized lock. Congress has authorized the project but it has not yet been funded.

MILITARY PRESENCE AT THE SOO LOCKS

During World War II, the Soo Locks were considered so vital to the war effort that the US Army garrisoned up to 20,000 troops there because of concerns about a German attack. The British and Canadians also garrisoned troops on their side of the border.[38] Searchlights dotted the area to protect the locks from an air attack. While an air attack was considered highly unlikely, Charles Lindbergh's crossing of the Atlantic Ocean was still fresh, raising the fear of a potential air assault. The biggest concern was an attack from the north; James Bay on the southern part of Hudson Bay, is only 400 miles from Sault Ste. Marie.

FIGURE 10—KOREAN WAR ERA SEACHLIGHTS

The searchlights were replaced during the Korean War and remain in place today (see Figure 10).[39]

During the Spanish-American War in 1898, parts of the Pennsylvania National Guard were ordered to Michigan to guard the Soo Locks.[40]

The Lakers were designed to make maximum use of the dimensions of the locks. The Poe Lock is 1,200 feet long and 110 feet wide and the One Thousand Footers are about 1,000 feet long and 105 feet wide. Unlike captains of ocean-going vessels, the Great Lakes captains pilot their ships without tugboats through congested rivers, the Soo Locks, or for docking. All vessels enter the locks under their own power, still without using a tugboat.[41]

> *"When you're on a ship coming into the locks, especially a thousand–footer, the lock's 110 feet wide, the ship is 105 feet wide, and from the pilot house, your perspective, it doesn't look like the ship will actually even fit into the lock. So it's kind of a unique experience. It's amazing to watch the skill of the captains when they bring these big ships into such a small area."*[42]

It takes a total of about 60 minutes to transit a lock, from the time a vessel approaches the lock until it leaves the lock. Once the vessel is secure within the locks, it takes 15–20 minutes to either raise or lower the vessel the 21-foot difference between Lake Superior and Lake Huron.[43]

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38 Lake Superior State University, "Pre-LSSU History: The Story of Fort Brady," at http://www.saultstemarie.com/lake-superior-state-university-405/, accessed March 5, 2015.
39 From the private collection of Dr. Craig S. Gordon.
40 Image and information from The National Son, "The 18th Pennsylvania Volunteer Infantry Regiment," Winter 2013, Volume VI, Number 2.
41 USACE, "Frequently Asked Soo Locks Questions," at http://www.lre.usace.army.mil/Missions/Recreation/SooLocksVisitorCenter/FrequentlyAskedSooLocksQuestions.aspx, accessed March 29, 2015.
42 Kevin Sprague, USACE Detroit District, "Soo Locks Opens Despite Ice," on March 26, 2015 at http://abc10up.com/soo-locks-open-despite-ice/, accessed March 29, 2015.
43 USACE, "Frequently Asked Soo Locks Questions," at http://www.lre.usace.army.mil/Missions/Recreation/SooLocksVisitorCenter/FrequentlyAskedSooLocksQuestions.aspx, accessed March 29, 2015.

The Soo Locks are purported to be among the busiest locks in the world.[44] Records from 2004–2013 indicate that the MacArthur Lock handles over 4,100 vessels per year, while the Poe Lock handles about 3,800 vessels.[45] On average, 15.2 vessels per day have 'locked through' the MacArthur Lock over the past 10 years, though over the past 3 years this has dropped to 13.7.[46] On average, 12.7 vessels per day have locked through the Poe Lock over the past 10 years.

U.S.-flagged vessels, which are subject to the Jones Act of 1920, dominate vessel movement through the Soo Locks.[47] Approximately 63 percent of the vessels locking through the MacArthur Lock and approximately 71 percent of the vessels locking through the Poe Lock are U.S.-flagged vessels. Canadian-flagged vessels constitute most of the other vessels. Canadian traffic has increased over the past 3 years because the configuration of the Canadian fleet has changed considerably. In 2010, the Canadian Government lifted a 25-percent tariff on Canadian-flagged vessels not built in Canada, which led to new orders and deliveries of vessels.[48] In 2011, the first new Canadian Lakers entered the fleet.[49] The new Lakers are Welland Canal-sized vessels, which are slightly too large for the MacArthur Lock.[50] This has led to a 25 percent decrease in the Canadian traffic through the MacArthur Lock as traffic shifted to the Poe Lock, a trend that is likely to continue as new Lakers enter the fleet.

FIGURE 11—THE SOO LOCKS

In addition to the four USACE locks, there is one Canadian Lock used for recreational vessels, located near the top of the graphic in Figure 11. Further, the Soo Locks complex houses two hydroelectric plants, the Sault Ste. Marie International Bridge that connects Sault Ste. Marie, Ontario to Sault Ste. Marie, Michigan, and a rail bridge. The hydroelectric plants provide all of the power needs of the Soo Locks complex and can provide black-start

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44 Michigan State University, "The Soo Locks," at http://geo.msu.edu/extra/geogmich/SOOLOCK.html, accessed January 2, 2015.
45 USACE, "Statistical Report of Lake Commerce Passing through St. Marys Falls Canal, Sault Ste. Marie, Michigan During the 2013 Navigation Season." Copies from 2004-2012 were also accessed.
46 After dropping the anomalous year of 2010. Including 2010 would raise the figure to 16.7.
47 The Jones Act, technically called the Merchant Marine Act of 1920 (P.L. 66-261), requires that all goods transported by water between U.S. ports be carried on U.S.-flagged ships, constructed in the U.S., owned by U.S. citizens (including corporations such as the Great Lakes Fleet, Inc. which is one of the 3 largest carriers on the Great Lakes and indirectly owned by Canadian National Railway), and crewed by U.S. citizens or residents.
48 The Bay Observer, "Removal of Tariff Unleashes $1 Billion Renewal of Great Lakes Fleet" on June 21, 2013 at http://bayobserver.ca/removal-of-tariff-unleashes-1-billion-renewal-of-great-lakes-fleet/, accessed May 8, 2015.
49 Boat Nerd, "Baie St. Paul (2)" at http://www.boatnerd.com/pictures/fleet/baiestpaul.htm, accessed May 8, 2015.
50 The Welland Canal is a series of 15 locks that connect Lake Erie and Lake Ontario with access thereafter to the Saint Lawrence Seaway and then the Atlantic Ocean.

capabilities in the event of a power outage in parts of the Upper Peninsula of Michigan.[51] Algoma Steel (Essar Steel) is located on the Lake Superior side of the Soo Locks on the Canadian side of the border.

STEEL MILLS – AUTOMOBILE MANUFACTURING

The relationship between the mills and the auto assembly plants is complex. Steel mills make various grades of steel to supply different markets and different categories within markets (see Appendix D for a list of products made with steel).[52] However, almost every steel mill makes some type of steel for the automotive industry, the market that dominates the steel industry.[53]

Automotive companies order specific grades of steel from specific mills for specific car parts. The resulting steel is then processed at a number of automotive parts manufacturers.[54] Industry executives reported that there are some 1,500 different recipes of steel for the automotive industry. Almost every part of a car made from steel uses a different type of steel. Industry executives explained that to certify steel for a particular use, automotive manufacturers may require one year to qualify, not just a particular grade of steel, but the path used to process the steel. Each steel mill manufactures steel for multiple cars and each car has steel from multiple plants. For these reasons, there is not a simple linear relationship from mine to mill to manufacturer.

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51 Black start is the procedure to recover from a total or partial shutdown of generation capacity supplying the transmission network. Many power stations require off-site power to restart operations, but black start facilities can be started without it. Each region of the U.S. has detailed black start plans and designated black start facilities. If there is a failure of the transmission network, resulting in widespread generation shutdowns, the black start power stations will be started and reconnected to the network first , so that other plants can be gradually brought back on line to form an interconnected system again (see Morris, Lindsay, Power Engineering Magazine, "Black Start Preparedness for Any Situation," July 1, 2011, at www.power-eng.com/articles/print/volume-115/issue-7/features/black-start-preparedness-for-any-situation.html, accessed June 22, 2015.)

52 Steel making is a multi-phased process beginning with the combining iron ore with various other materials that include limestone, coking coal, and oxygen in a blast furnace. At temperatures in excess of 3000 degrees, the blast furnace produces molten iron. The molten iron moves to a basic oxygen furnace that combines the molten iron with oxygen, some scrap steel, and other chemicals to make molten steel. The slab casting facility takes the molten steel and turns it into a slab, which is a rectangular-shaped block more than 6 inches thick. The slabs generally go to one or more rolling facilities that turns the slab into a thin coil of steel ranging from 1/16th inch to 1/2 inch thick though the slabs could go to a plate mill to make steel plates.

53 The primary steel market is for automobiles, followed by construction, machinery and equipment, pipelines to move energy products, packaging containers, appliances, and national defense. A large percentage of steel is sold to steel distribution centers that sell to smaller manufacturers, contractors, and local governments.

54 The parts of the car typically made out of steel include auto body (except the hood on some cars that is made of aluminum), chassis, suspension modules, engine block (this could be aluminum on some cars), drive shafts, rails for seats, underneath crash pad, door beam, and the steering column.

HISTORY OF THE SOO LOCKS

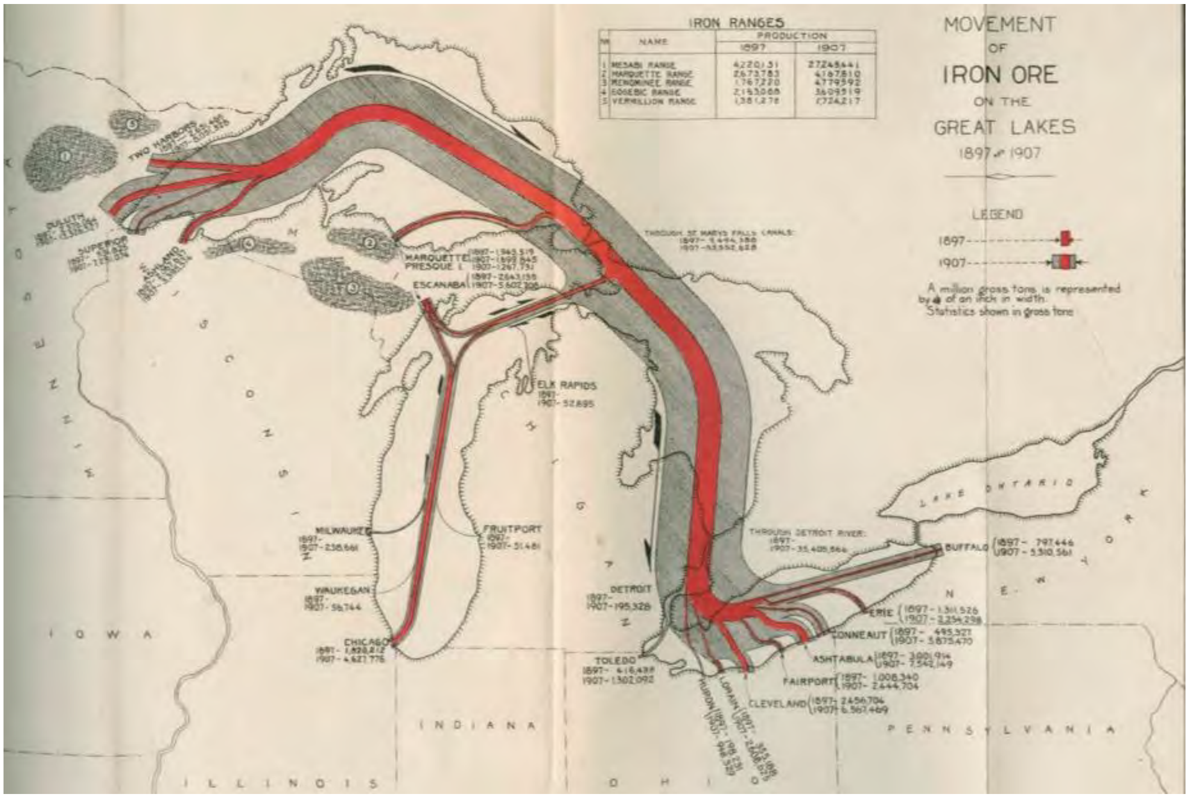

FIGURE 12—HISTORICAL DOCUMENT SHOWING MOVEMENT OF IRON ORE IN 1897 AND 1907[55]

The iron ore-steel-manufacturing supply chain that passes through the Soo Locks has operated essentially uninterrupted and unchanged for 160 years and may account for both its efficiency and lack of resilience. On August 17, 1855, the two-masted brigantine Columbia, left Marquette, MI on Lake Superior, sailed down Saint Marys River, locked through the new State Lock at the Soo Locks, transited Lake Huron, and docked in Cleveland. From Cleveland, the Columbia's cargo of 132 tons of iron ore went by rail to an iron smelter near Pittsburgh. This was the first shipment of iron ore to pass through the Soo Locks.

Figures 12 and 13 show historical maps to illustrate how stable these routes have been over time. The red line in Figure 12 shows the routes and the relative amount of iron ore shipped through the Great Lakes in 1897. The grey line in Figure 12 shows the increased volume of iron ore moved along these routes in 1907. Figure 13 shows the movement of commodities in 1940 (iron ore is shown in orange). Only two significant changes to the supply chain exist today. The Wisconsin iron ore ports (other than the port in Superior, WI) migrated to Minnesota, and the destination for the iron ore has generally moved west from Lake Erie to Lake Michigan. As one industry executive explained, the rationalization of the steel industry during the period 1970-2000 impacted the steel mills on Lake Erie to a greater extent; the likelihood that a steel mill would close was directly proportional to its distance from Minnesota. [56]

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[55] Map reproduced from "Report of the Commissioner of Corporations on Transportation by Water in the United States," Volume 2, 1909, opposite p. 156, via Nekola Peter and Dugre, Neal, The Newberry: Digital Collections for the Classroom, Web page "Commodities and the Transformation of the American Landscape," 2014, at http://dcc.newberry.org/collections/commodities-and-the-transformation-of-the-american-landscape, accessed May 18, 2015.
[56] Much of the information obtained for this report came from people associated with the broader supply chain. Everyone we spoke with provided very candid and open assessments, for which we are extremely grateful, and we agreed that we would not disclose any identifying information. Any reference to 'industry executive' in this report covers these frank discussions.

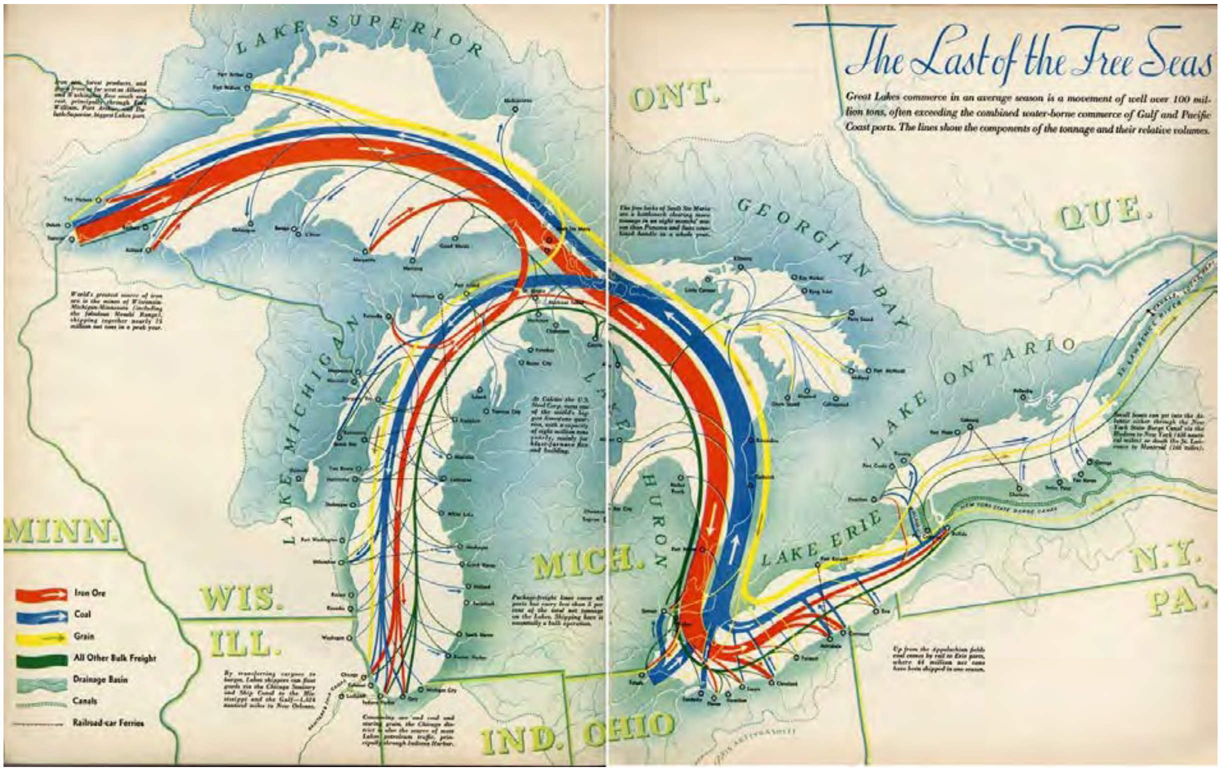

FIGURE 13—HISTORICAL DOCUMENT SHOWING MOVEMENT OF IRON ORE IN 1940[57]

From the time of the Columbia's first shipment, through the explosion of industrialization around the Great Lakes, the amount of iron ore moving by water increased rapidly, as the cost of waterborne transportation dropped in comparison to the cost of shipping by rail. In 1884, about 2.3 million tons of iron ore were shipped from Lake Superior iron ore docks to the Great Lakes steel mills.[58] By 1898, the volume had increased almost 6-fold. Vessel rates, which started at about $3 per ton to move iron ore in 1856 dropped 83 percent to $0.50 by 1897.[59] During the same period, rail rates decreased, but not nearly by the same degree or same rate. By 1907, moving iron ore by vessel saved the steel mills $173 million over moving iron ore by rail; iron ore could be shipped from Lake Superior to Lake Erie at one-seventh the cost of the shipping iron ore from Lake Erie to Pittsburgh.[60,61] As the February 6, 1902 Marine Review stated, "the cost of water carriage by the introduction of larger vessels… has been greatly reduced, while that by rail has not been lessened materially. The savings is, therefore, greater than ever."[62]

About half of the integrated steel mills that make automotive quality steel today were built during this period of industrialization.[63] These steel mills, and others built as late as the mid-1960s, were constructed without an ability to receive iron ore by rail. The cost differential between rail and vessel was such that a rail option was not considered necessary.

The decision to forgo a rail option meant that the supply chain relied on the Soo Locks to operate, without fail. There has never been a long-term failure of the Soo Locks, which has led to an assumption that the Soo Locks will operate indefinitely without a major failure. As one industry executive put it, users expect that "the Soo Locks will operate just as the sun rises every day." One reason for the 160 years of uninterrupted service may be that new

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57 Artyzbasheff, Boris, "The Last of the Free Seas," Fortune Magazine, July 1940, via "Visual Telling of Stories" Web site, at http://www.fulltable.com/VTS/f/fortune/xa/75.jpg, accessed May 12, 2015.
58 Mansfield, J.B., "History of the Great Lakes," Chicago: J.H. Beers & Co. 1899.
59 Ibid.
60 Curwood, James O., "The Great Lakes: The Vessels that Plough Them: Their Owners, Their Sailors, and Their Cargoes. New York: G.P. Putnam, 1909.
61 The $173 million dollar figure comes from the above referenced book written in 1909.
62 Bowlus, W. Bruce, "Iron Ore Transport on the Great Lakes," McFarland: Freemont, OH, 2009.
63 Rouge Steel (now AK Steel Dearborn) was built in 1915, Indiana Harbor in 1901, Gary Works in 1906, Great Lake Works in 1902, and Cleveland in the 1880s.

locks were added at regular intervals from the initial building of the Soo Locks through the rebuilding of the Poe Lock in 1968. As Table 2 shows, from the time that the State Lock opened in 1855 through the rebuilding of the Poe Lock, a lock was built or rebuilt every 19 years, on average. During this period, the longest span without a lock addition or replacement was the 26 years between the building of the State Lock (1855) and the building of the Weitzel Lock (1881). Since the rebuilding of the Poe Lock (1968), 47 years have elapsed without a new lock or a lock rebuild, almost twice as long as the previous longest gap.

TABLE 2—THE HISTORICAL LOCKS AT THE SOO LOCKS[64]

Lock	Year Opened	Measurements	Depth	Year Closed	Years in Service	Years Since Last Lock Construction
State Lock	1855	350' x 70'	12'	1888	33	-
Weitzel Lock	1881	515' x 80'	18'	1943	28[65]	26
Poe Lock	1896	800' x 100'	21'	1954	23[66]	15
Davis Lock	1914	1350' x 80'	24'	2008	94[67]	18
Sabin Lock	1919	1350' x 80'	24'	1989	70	5
MacArthur Lock	1943	800' x 80'	29 ½'	-	72+	24
Poe Lock (rebuilt)	1968	1200' x 110'	32'	-	47+	25

GREAT LAKES NAVIGATION SEASON

FIGURE 14—THE GREAT LAKES TRANSPORT DURING THE WINTER[68]

The Locks close during the winter due to the harsh weather conditions (see Figure 14), which allows for maintenance and repairs to both the locks and the Lakers. Traditionally, the Soo Locks navigation season has been from approximately March 25–January 15, lasting about 297 days.[69] Since at least 2004, the MacArthur Lock navigation season has, on average, shortened by about 3 days per year. Since at least 2004, the MacArthur Lock has delayed its opening until about April 9 and has closed earlier than the Poe Lock, generally around December 23.[70] The MacArthur Lock navigation season is now about 252 days long, or about 1.5 months shorter than Poe Lock's navigation season.

There are important differences in shipping patterns between Poe-restricted Lakers and the MacArthur-sized Lakers. On average, there are roughly 16 passages per day through the MacArthur Lock, compared to fewer than

[64] USACE, "Soo Locks History," at http://www.lre.usace.army.mil/Missions/Recreation/SooLocksVisitorCenter/SooLocksHistory.aspx, accessed April 26, 2015.
[65] While the Weitzel Lock did not formally close until the building of the MacArthur Lock in 1943, after 1919, the lock was rarely used.
[66] While the original Poe Lock remained until 1954, suggesting 58 years of service, the USACE reported that, after the opening of the Sabin Lock in 1919, "no significant tonnage passed the old Poe Lock (email, June 7, 2015 at 1:28p)."
[67] The Davis Lock is technically still operational, but has not been used since 2008.
[68] Photo source U.S. Coast Guard, January 9, 2014, via Phys.org Web page "Great Lakes Become Nearly Covered with Ice," February 15, 2014, at http://phys.org/news/2014-02-great-lakes-ice.html, accessed May 18, 2015.
[69] The information herein comes from the 2004-2012 Traffic Statements, St. Marys Falls Canal, Sault Ste. Marie, Michigan.
[70] The average opening day excludes a significantly later opening in 2009. This delay may have been due to the economic downturn that decreased the number of vessels transiting the Soo Locks and allowed USACE to extend its maintenance season.

13 per day through the Poe Lock, even though there are 40 percent more Lakers that must use the Poe Lock than can use the MacArthur Lock (see Appendix C). This is because the Poe-restricted Lakers each make about 50 long trips per year, from Lake Superior to steel mills and coal-fired electric power generation facilities along Lake Michigan, Lake Erie, and Detroit. In contrast, the MacArthur-sized Lakers may each make about 85 shorter trips per year, carrying a wider variety of commodities downstream through the Soo Locks and limestone upstream.

The three most critical months for shipping iron ore are May, June, and July. Total shipments during these months are almost 18 percent higher than for the three-month period October through December. The May–July period has better weather and higher water levels.[71,72] Water in the Great Lakes is highest from June through August, meaning that ships can be more fully loaded. At this time of year, water levels average about 22 inches above the chart datum of 577.5 feet on Lakes Michigan and Huron.[73] Thereafter, the water levels drop by about 2 inches per month before reaching their lowest levels in February. Each inch of draft lost by the largest Lakers decreases the cargo that the vessel can move by about 200 tons.[74,75]

Seasonal ice, winds, and storms affect shipping on the Great Lakes. Before May, shipping can be difficult due to ice conditions, as exemplified during March–April 2014 when almost all of the Great Lakes froze. (In March 2014, 92 percent of the Great Lakes froze, the second highest total on record.[76] In April 2014, nearly 67 percent of the Great Lakes remained frozen.) Starting in September, the winds become challenging, slowing the shipping process. In late October, the weather cools significantly and the storms become more severe.

November is a particularly bad month for weather with some of the fiercest storms occurring including the two worst ever recorded, the Great Storm of 1913 and the Armistice Day Storm in 1940.[77] The sinking of the Edmund Fitzgerald, made famous in popular music, occurred during a storm in November 1975. [78]

Inventories on each side of the locks rise and fall in a seasonal pattern, as the iron mines, shippers, and steel mills plan and work around the winter closure of the locks. During the seasonal closure of the locks, the iron mines continue to extract iron ore and move it to the docks, where they build inventory until the navigation season recommences. At full capacity, the iron ore docks hold about 15 million tons. By the time the navigation season closes, all of this iron ore should have been moved from the docks to the mills, building up the excess inventory at the mills.

During the winter, while the iron ore mines are building up inventory at the docks, the steel mills are drawing down their on-site inventory built during the previous navigation season.[79] When the locks reopen, the steel mills may have only a few weeks' worth of inventory remaining. The relatively low levels of inventory remaining after the winter closure of the Soo Locks was demonstrated in April 2014, when remaining ice from the severe winter effectively delayed the Soo Locks opening by 2 weeks.[80] Gary Works (U.S. Steel) had to curtail production during the first week of April due to a lack of iron ore.[81]

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71 Escanaba's shipping season is almost diametrically opposite. The high season for shipping out of Escanaba is December – January and the low season is August – September. The large vessels generally will not visit Escanaba when the Soo Locks is open and Escanaba can continue to ship when conditions on Lake Superior and Lake Huron are more difficult.

72 Trying to extend the shipping season is problematic as the ice can damage the vessels and potentially have negative environmental impacts.

73 USACE, "Lakes Michigan-Huron Water Levels – June 2015," on June 5, 2015 at http://w3.lre.usace.army.mil/hh/ForecastData/MBOGLWL-mich_hrn.pdf, accessed June 8, 2015.

74 Lake Carriers Association, "Dredging Crisis," on April 23, 2013 at http://www.lcaships.com/2013/04/23/dredging-crisis/, accessed June 8, 2015.

75 Thompson, Mark L. "Steamboats & Sailors of the Great Lakes," Wayne State University Press: Detroit, 1991.

76 NOAA, "National Overview – March 2014 Great Lakes Ice," at https://www.ncdc.noaa.gov/sotc/national/2014/3/supplemental/page-4/, accessed June 22, 2015.

77 Joachim, George J., "Iron Fleet: The Great Lakes in World War II," Wayne State University Press: Detroit, 1994.

78 Gordon Lightfoot, "Wreck of The Edmund Fitzgerald - Gordon Lightfoot Song Lyrics," at http://gordonlightfoot.com/wreckoftheedmundfitzgerald.shtml, accessed June 24, 2015.

79 Typically, the taconite is pelletized at the mines before being transported to the docks. None of the iron ore is stored at the mines as there is no economic benefit to maintaining inventory there. At the docks, iron ore may be segregated by grade and destination, some of which may be interchangeable between steel mills.

80 The Locks did open on time, but the vessels could not operate due to the icy conditions. The Lakers, which generally take 2 1/2 days to transit Lake Superior, were at sea for 9 days in Lake Superior following two icebreakers (see Figure 13).

81 The Times, "Steelmaking idled at Gary Works," on April 4, 2014, at www.nwitimes.com/business/local/steelmaking-idled-at-gary-works/article_089e0dcf-c395-5d95-b151-457d90c23839.html?print=true&cid=print, accessed January 2, 2014.

Supply disruptions can occur for reasons other than weather. Also in April 2014, Great Lakes Works (U.S. Steel) declared force majeure related to a crane collapse involving repair work.[82] Reports indicated that, "at least one automaker has reportedly started to examine possible [supply] shortages related to the U.S. Steel situation."[83] To restore normal production required two months from the time that Great Lakes Works restarted full operations.

[82] Found in most commercial contracts, force majeure frees either party from liability in the event there are circumstances beyond ones control (e.g., fire destroying a manufacturing plant so that products cannot be manufactured and supplied).
[83] Platts, "Force Majeure Events at US Steel's Great Lakes Works Could Disrupt Supply," on April 11, 2014 at http://www.platts.com/latest-news/metals/pittsburgh/force-majeure-events-at-us-steels-great-lakes-21470889, accessed March 11, 2015.

POTENTIAL IMPACTS DUE TO A CLOSURE SCENARIO

The impact to the iron mining—integrated steel production— automobile manufacturing supply chain would occur quickly if the Poe Lock were to remain closed at the start of the new navigation season due to an event that lasted about 6 months.[84,85] The scenario closure used in this analysis lasts from March 25– September 25. In order to determine the impacts of a potential closure scenario, OCIA-NISAC reviewed the supply chains for each of the iron ore mines and steel mills to determine which mines and mills were likely to operate and at what level, and confirmed the general assessment with industry executives. The assessments herein are based on reasonable assumptions about what would likely happen; in the event of a real unanticipated closure, the actual impacts are likely to differ.[86,87]

[84] All industry experts expressed concern about a potential longer-term failure of the Soo Locks. Some indicated that they awake each day and cross their fingers that the Soo Locks will operate that day. It should be noted that the Soo Locks has consistently and reliably operated.

[85] While the scenario discussed herein is a 6-month closure, major disruptions would occur even with a significantly shorter disruption.

[86] The 6-month closure scenario was selected as a plausible length of time that is long enough to have significant impacts. No specific damage is assumed. Steel mill closures of less than 1 month do cause some minor disruptions and some automobile manufacturers may have to curtail production for short periods. However, the impact to the U.S. economy would likely not be noticeable. A closure of 1 year or more would cause far more dramatic economic impacts than estimated here. Longer outages would likely force the various industries involved in this supply chain to make lasting operational changes, which are outside the scope of this analysis.

[87] The original assumption was that a 6-month closure at the start of the shipping season would be the worst possible timing. Therefore, this scenario was selected to establish the upper bound of consequences. However, subsequent research suggests that a closure at the start of the navigation season may not be the worst case. The analysis herein suggests that a 6-month closure scenario at the start of the navigation season on March 25 would lead to production stopping around April 15 and re-starting around December 15. This would allow steel mills to have enough iron ore on hand to get through the winter. This implies a steel shutdown of about 244 days. On the other hand, later in the shipping season, around September 1, may represent the "best" time for closure. At this point, the integrated steel mills would have built up their winter supply; shipments that arrive between September 1 and January 15 generally meet current demand. As the steel mills have about 2 months of supply on hand, the September 1 shutdown would mean a closure of the mills around November 1. No iron ore would start arriving at the steel mills until March 25, when the Soo Locks would normally re-open for the new navigation season. Our assumption in this case is that, by May 1, there would be sufficient inventory at the steel mills to re-start production. This implies a steel shutdown of about 182 days. The worst-case scenario likely would be a closure that started between May 1 and July 15, because there would be no way for steel mills to restock before the winter closure. For example, if the Locks closed on June 1, there would be the beginnings of extra inventory from shipments delivered between March 25 and June 1. Our assumption is that, on June 1, there would be a 35-day inventory, which means that, if the Soo Locks closed on June 1, steel production would end around July 4. The problem is at the other end. A June 1 shutdown would mean a December 1 re-open; however, there is no way to get enough iron ore to the steel mills before the winter closure of the Soo Locks to allow production to recommence. Our estimate is that there would not be sufficient inventory until about April 15, which implies a 284 day closure. Still, a "best case scenario" would have significant unemployment impacts as described in the section entitled, "Potential Economic Impacts," though the GDP impacts would be less severe due to the shorter disruption period.

IRON ORE MINING ASSUMPTIONS

FIGURE 15—IRON ORE MINES AND PORTS

Overall, about 78 percent of the domestic iron ore capacity is expected to shutter for the duration of the scenario.[88]

Some mining operations would likely continue in both Michigan and Minnesota under a lock closure scenario. Forty-six percent of the 15.2 million tons of the rated iron ore mining capacity in Michigan would remain operational in a closure scenario (see Figure 15 for the locations of the iron ore mines).[89] This calculation is based on the assumptions that the Empire Mine could continue to operate through the Port of Escanaba, as it currently does, and that the Tilden Mine would operate at a level to support the Algoma Steel Mill (Essar Steel), which is the only steel mill on Lake Superior and to meet the surge capabilities at the Port of Escanaba. Likewise, 16 percent of the 48.5 million tons of annual capacity in Minnesota would remain operational in a closure scenario, based on the assumption that iron ore that currently moves by rail to steel mills could continue to be mined and transported (see Table 3 for a list of operational and non-operational mines).

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[88] Iron ore is mined throughout the winter and moved to the ports for transportation when the new navigation season begins. Once the pellets have been moved to the docks, they become stranded. The docks are designed to receive iron ore by rail or truck and to move the iron ore out by vessel. There is no equipment at the docks to load iron ore onto rail for further movement. If one could move the pellets out, then new mining activity would drop to 0 as there is likely a sufficient stock of pellets at the mines to meet the demand of the steel mills remaining in operation.

[89] These figures assume that, unless otherwise specified, rated capacity and production are assumed to be the same. The operating mines, quarries, mills, and factories generally are operating at full capacity under the current economic conditions. However, as will be discussed, the two mines in Michigan are not operating at their rated capacities.

TABLE 3—IRON MINE EXPECTED OPERATING STATUS

Operating Mines			Non-operating Mines or Portions of Mines not Operating		
State	Mine	Capacity (mm tons)	State	Mine	Capacity (mm tons)
Michigan	Empire Mine	2.5	Michigan	Empire Mine	3.7[90]
	Tilden Mine[91,92]	4.5		Tilden Mine	4.5[93]
Michigan Total		7.0			8.2
Minnesota	Bovey[94]	1.2	Minnesota	Hibbing Taconite	9.0
	Keewatin[95]	0.4		Minntac	16.0
	Keetac[96]	6.0		United Taconite	5.9
				Minorca Mine	3.1
				Northshore Mining	6.9
Minnesota Totals		7.6			40.9

All of the iron ore pellets that had been extracted, pelletized, and moved to the iron ore ports in Minnesota in preparation for the March 25 opening of the navigation season would likely be orphaned if the Poe Lock was not operating.[97] There is no feasible way to move this iron ore out of the iron ore docks by any means other than by Laker. While the Duluth-Superior docks evidently have limited capacity to load rail cars, the terrain surrounding Duluth-Superior, Two Harbors, and Silver Bay makes it impractical to move iron ore by rail out of the port facilities. The challenge is that all of the mines are in the mountainous parts of Minnesota, with the decline most pronounced near the ports. Within a couple of miles of the docks, the elevation changes more than 500 feet. Locomotives could only pull up a few railcars of iron ore at any one time. Therefore, any steel mills still in operation after the scenario closure would require new production from the mines. However, the Minnesota mines still in operation could be hampered by a lack of limestone moving upstream through the Soo Locks, if the MacArthur Lock were also closed. This limestone is necessary for the pelletizing of iron ore.[98]

Limestone deliveries could continue if only the Poe Lock closed. Far less limestone is required to move upstream, as the iron ore-to-limestone ratio is about 9:1.[99] Further, limestone is far less dense than iron ore and there are more options to deliver limestone to the pelletizing plants. In the event of a MacArthur Lock closure, limestone could be dropped in Green Bay, Wisconsin, Manitowoc, Wisconsin, or Cleveland, Wisconsin and railed to the pelletizing plant. There may be some capacity to rail limestone directly from Port Inland, Michigan, a major limestone quarry, to pelletizing plants.

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90 Empire Mine's rated capacity is 6.2 million tons, but is nearing the end of its productive life and produces at far lower rates (per Industry Executive). Therefore, the 3.7 million tons listed as "Non-operating" may not be available.
91 The Tilden Mine (Cliffs Natural Resources, US Steel) could also ship out of Escanaba.
92 Tilden Mine supports Algoma Steel (Essar Steel), which is located on the upbound side of the Soo Locks and Tilden Mine could continue to ship iron ore from the Port of Presque Isle/Marquette to Algoma. Data reviewed by OCIA-NISAC suggests that Algoma receives about 1.5 million tons of iron ore from Tilden Mine and an additional 3.0 million tons could be mined and shipped through Escanaba. This would represent a rate equal to the surge capacity.
93 Tilden Mine's rated capacity is 8.0 million tons, but has been producing at lower levels (per Industry Executive). Therefore, not all of the 4.5 million tons listed as "Non-operating" may be available.
94 The owner of the Bovey and Keewatin mines filed for bankruptcy on May 6, 2015. Keewatin's operations were idled previously and A.K. Steel, the part owner of the Magnetation operations and the sole customer was reported to have announced that it will limit its relationship with Magnetation and investigate other iron ore sources because of Magnetation's "near-term liquidity issues." This suggests that Magnetation's ability to survive bankruptcy may be challenging. (see Forum News Services, "Grand Rapids-based Magnetation mining files for bankruptcy" on May 6, 2015 at http://www.twincities.com/business/ci_28052217/grand-rapids-based-magnetation-mining-files-bankruptcy, accessed May 6, 2015.
95 See previous footnote.
96 Keetac will be idled in May 2015 due to a glut of iron ore and steel.
97 There would be no orphaned iron ore in Michigan. The Port of Escanaba could still operate and the Port in Marquette, Michigan does not have any storage facilities.
98 A number of the steel mills have sinter plants that can take iron ore particles and convert them into usable products at the steel mill. However, sinter generally is used for a relatively small amount of the iron ore, possibly about 5 percent.
99 For making flux pellets.

STEEL MANUFACTURING ASSUMPTIONS

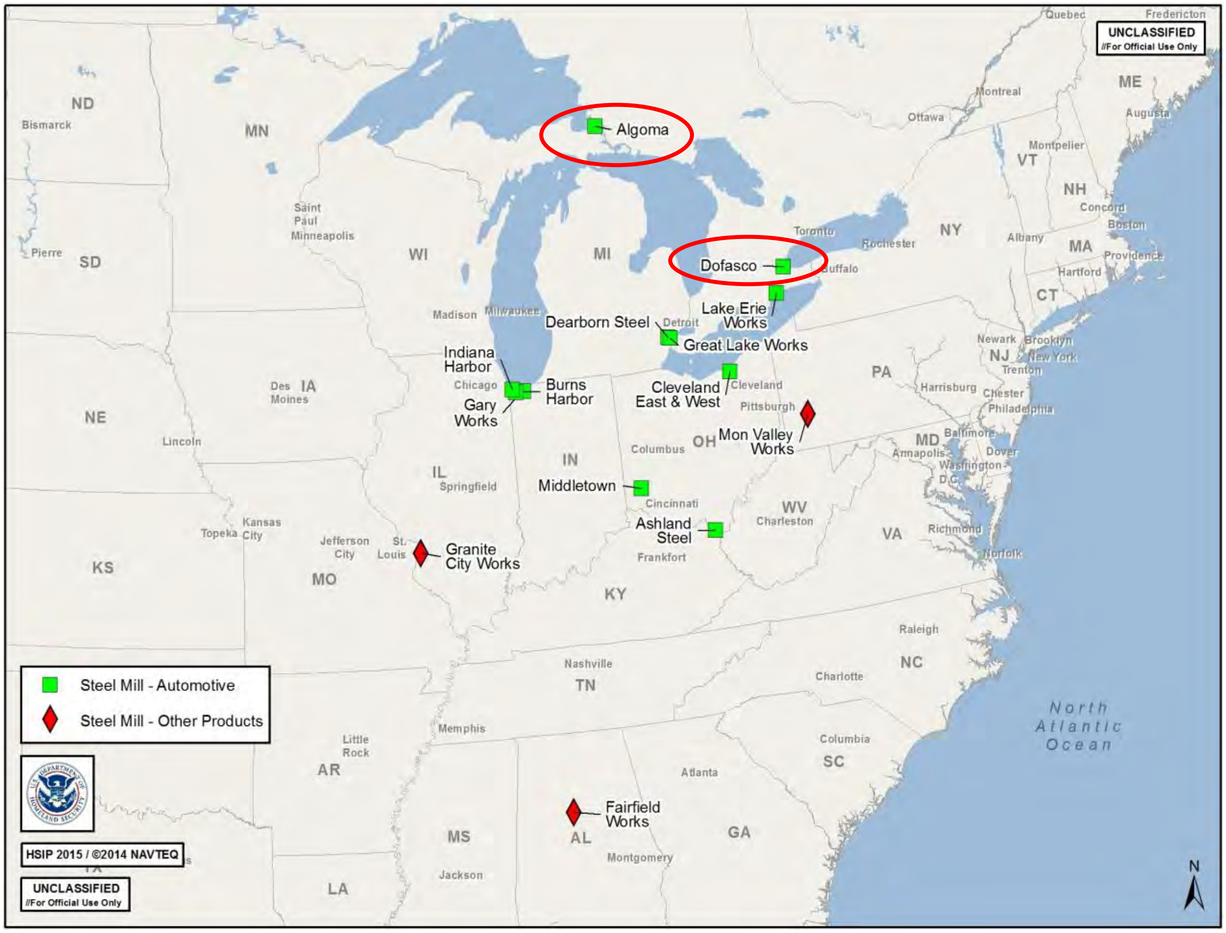

FIGURE 16—STEEL MILLS

The estimated total integrated steel production in North America is 57.5 million tons. Table 4 shows which steel mills OCIA-NISAC believes could continue to operate and which are likely not to operate due to a lack of iron ore (see Figure 16 for a map of the steel mills). In this Soo Locks closure scenario, 74 percent of the integrated steel production will shut down. More concerning, the steel mills that would shut down are, as a whole, more critical in the manufacturing of appliances, automobiles, construction, farming, and mining equipment, and railcar manufacturing than the steel mills that could continue to operate. Among the steel mills that could continue to operate, Fairfield Works (U.S. Steel) produces steel for the construction and tubular markets, Granite City Works (U.S. Steel) for the tubular market, and Algoma (Essar Steel), while it produces steel for the automotive market, does not produce the high strength—low weight steel most in demand.[100] Fairfield Works and Granite City Works receive their iron ore, by rail, directly from Minnesota, while Algoma is the only steel mill on Lake Superior. Therefore, the iron ore does not need to transit the Soo Locks.

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[100] Fairfield Works (U.S. Steel) is also installing an electric arc furnace where the existing blast furnace is located (P.R. Newswire, "U. S. Steel Announces Construction Of Electric Arc Furnace And Tubular Products Coupling Facility In Jefferson County, Alabama," on March 19, 2015 at http://www.prnewswire.com/news-releases/u-s-steel-announces-construction-of-electric-arc-furnace-and-tubular-products-coupling-facility-in-jefferson-county-alabama-300053140.html, accessed June 15, 2015.

TABLE 4—STEEL MILL OPERATING STATUS DURING A POE LOCK CLOSURE

Operating Steel Mills			Non-operating Steel Mills		
State / Province	Mine	Capacity (mm tons)	State / Province	Mine	Capacity (mm tons)
Alabama	Fairfield Works[101]	2.4			
Illinois	Granite City Works[102]	2.8			
			Indiana	Burns Harbor	5.0
				Gary Works	7.5
				Indiana Harbor[103]	9.5
			Kentucky	Ashland	2.6
			Michigan	Dearborn	2.5
				Great Lake Works	3.8
Ohio			Ohio	Cleveland	3.8
	Middletown[104]	2.4		Middletown	0.5
Ontario	Algoma	2.8	Ontario	Lake Erie Works	3.7
	Dofasco	4.5			
			Pennsylvania	Mon Valley Works	2.9

To make the full complement of car models available in North America today, all of the steel mills listed as "Non-operating Steel Mills" in Table 4 must be operating, other than Mon Valley Works (U.S. Steel), which primarily makes steel for the appliance industry.[105] In Figure 16, the steel mills that produce steel for the automotive industry are marked by green boxes. The two steel mills that would still operate, Algoma (Essar Steel) in Sault Ste. Marie, Ontario and Dofasco (ArcelorMittal) in Hamilton, Ontario are indicated by a red circle. As discussed in the Background section, the integrated steel – automotive supply chain is complicated, and most steel mills produce steel for parts of most automotive lines. Based on discussions with industry executives, to make any automobiles in North America, the three Indiana steel mills must be operational and some combination of three of the remaining six steel mills. If one steel mill is not operational, some automotive *lines* are not likely to be functioning; if two steel mills are not operational, some automotive *companies* may not be able to make automobiles.

Table 5 provides the per-State estimate for steel production remaining after the closure scenario, which is the proxy used for employment.

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101 U.S. Steel announced that it plans to close Fairfield Works and re-open it as a mini-mill (see NPR, "U.S. Steel to End Operations at Alabama's Fairfield Works Mill," on August 18, 2015 at www.npr.org/2015/08/18/432683704/u-s-steel-to-end-operations-at-alabamas-fairfield-works-mill, accessed October 13, 2015).

102 Granite City Works (U.S. Steel) has been temporarily idled due to lack of demand for tubular products because of the decrease in petroleum prices. Our analysis assumes a 'normal' economic environment where Granite City would be operational. Granite City sources its iron ore from Keetac. Further, the REMI Model used to calculate the economic impact is based on an environment where Granite City Works was not idled.

103 Indiana Harbor receives the majority of the iron ore shipped out of Escanaba, which means that it could operate. However, the amount of iron ore shipped out of Escanaba is not likely sufficient to operate. Industry analysts and management consultants suggest that steel mills will not operate at less than 70-85 percent capacity utilization as it is not profitable below that level (see The Globe and Mail, "U.S. Steel Shutting Hamilton Mill," on October 1, 2010, at www.theglobeandmail.com/report-on-business/us-steel-shutting-hamilton-mill/article4329666/, accessed January 27, 2015 and Boston Consulting Group, "Flexibility: Streamlining Production," at www.bcgperspectives.com/content/articles/metals_mining_sourcing_procurement_flexibility_innovation_todays_imperatives_steel/?chapter=2, accessed January 15, 2015.) One industry executive stated that it is "technically impossible for a blast furnace to run at less than 70 percent," which would be the case.

104 Based on our analysis of the Middletown supply chain, OCIA-NISAC estimates that Middletown could only receive 82 percent of its needs from the Magnetation mines (see footnote 90) and from Escanaba.

105 In order to make appliances in North America, Mon Valley Works (U.S. Steel) must be operational.

TABLE 5—STEEL PRODUCTION BY STATE

State or Province	Steel Manufacturing Still Operational
Alabama	100.0%
Illinois	100.0%
Indiana	0.0%
Kentucky	0.0%
Michigan	0.0%
Ohio	35.8%
Ontario	70.4%
Pennsylvania	0.0%

The supply chain challenge is more complex than just moving iron ore to the integrated steel mills. For example, if steel mills could accept new sources of iron ore, disruptions to other supply chains could result. Blast furnaces are configured to take a specific iron ore pellet of a particular size that is either a standard or a flux pellet, mixed with a particular calcite/dolomite blend of limestone, trace elements and other chemicals, and metallurgical coal from a particular mine. Changing the iron ore pellets may require obtaining new limestone, trace elements and chemicals, or metallurgical coal products from new suppliers and testing the final products to ensure compatibility to the needs of the firm purchasing the steel.

AUTOMOTIVE MANUFACTURING ASSUMPTIONS

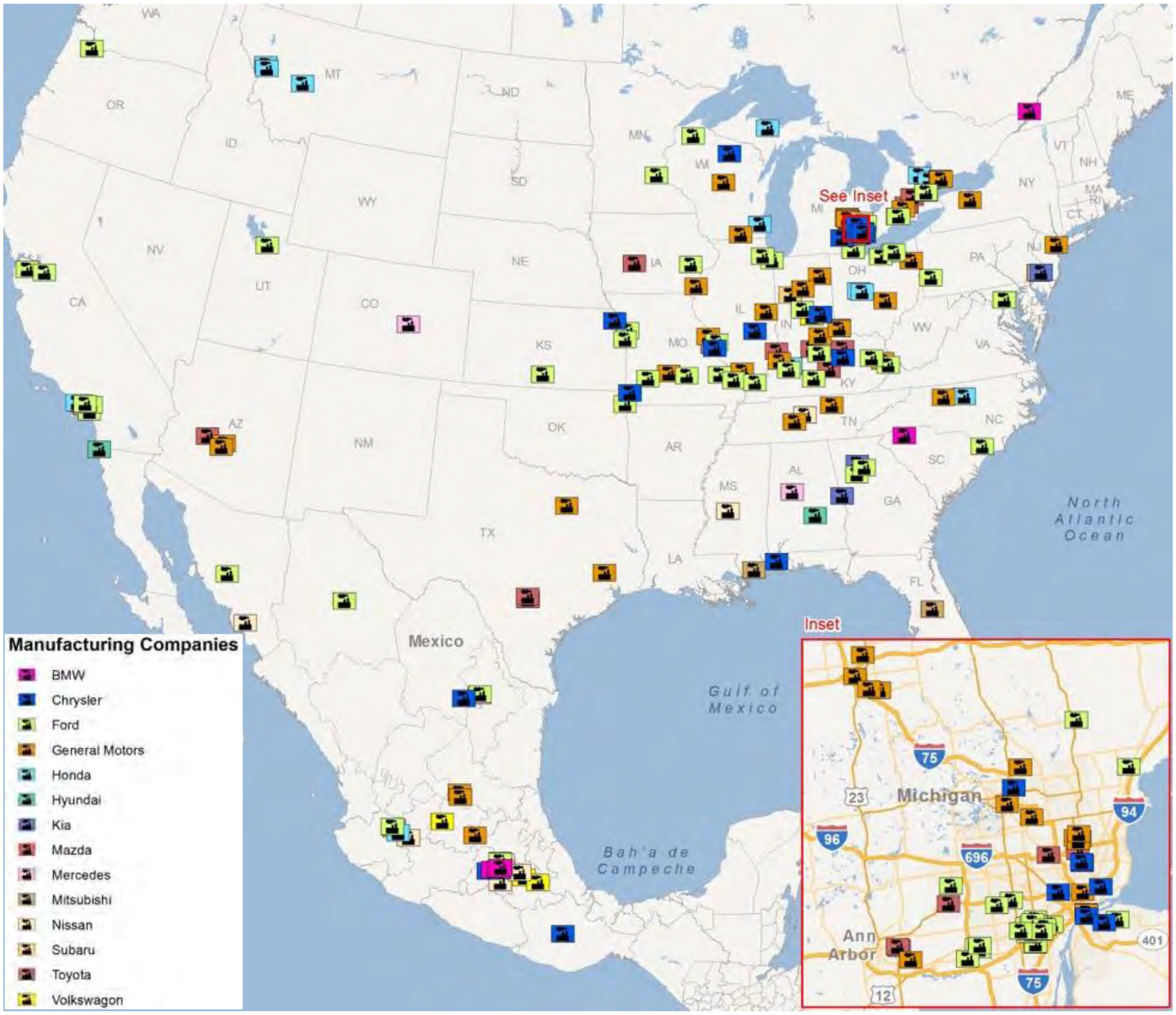

FIGURE 17—LOCATION OF AUTOMOTIVE MANUFACTURING PLANTS

An extended closure of the Poe Lock, which OCIA-NISAC assumes to be 6-months, would be extremely detrimental to the North American automotive industry including Canada and Mexico. Almost all North American automobile production would cease, and, in addition to the automotive industry, other industries that depend on steel including farm, mining, and construction equipment manufacturing, railroad locomotive and railcar production, and appliances.[106,107] As Figure 17 shows, most of the automotive manufacturing plants are located between Michigan and Ontario, Canada and south to Alabama. There are plants located in various other parts of the United States. Further, many automotive firms have plants in Mexico, most of which have supply chains highly integrated with the Canadian-United States supply chains.[108] According to industry executives, all of the

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106 An automotive expert stated, "[automobile] operations would shut down once the ore supplies were depleted and the normal steel and part buffers were exhausted. This would happen on a part-by-part basis and we do not have a good estimate of that timing. Our best guess is that it would happen within a few weeks. Yes, we would look to other non-domestic supply, but would be highly unlikely that we could secure enough material in the right specifications and quantities to support our volumes. This will impact all operations in North America and some operations across the globe." The global impacts of a potential shutdown have not been considered in this analysis.

107 The construction industry would not likely be impacted. Most steel used in construction comes from EAF mills and, to the extent that the BOF mills operate, they will likely have to sell their steel into the construction and tubular markets.

108 While OCIA-NISAC did not estimate an impact to the Mexican economy, published reports suggest that the automotive sector may account for about 3.25 percent of their economy, which is approximately the same percentage that the auto industry is in the U.S. economy, and higher than the auto industry contribution

automotive plants shown on Figure 17 use steel from at least one of the nine steel mills that make automotive quality steel.

Only a small percentage of North American auto manufacturing may be able to continue production after the disruption scenario. Some industry executives reported that one Volkswagen plant and one Nissan plant in Mexico sources its steel in Mexico. These plants would be able to maintain operations only if they source all other auto parts requiring steel from sources outside of North America, which is not likely. The BMW and Mercedes Benz plants located in the southeastern United States may be less impacted, if they can import all parts from Europe and only assemble automobiles in the United States. The disruption scenario will affect all other automotive plants.

According to industry experts, short-term disruptions of a single steel mill can cause disruptions throughout the North American supply chain. Firms must scramble to find alternative suppliers and to begin managing the process, part-by-part, to extend production times for at least some of their lines. Eventually, keeping the system going becomes impossible and lines shut down due to the lack of a single component. It could take more than 2 months to resupply the supply chain with enough steel-based product to restart production from the loss of a single steel mill. Lead times for many automotive parts are typically 8 – 14 weeks. However, regarding the current scenario, one industry expert said, "it's all done if all of the steel mills shut down."

The average age of automobiles on the road today is about 11.4 years.[109] This is consistent with average ages over the past few years and expectations over the next three years. A disruption scenario would lead to an increase in the average age based on the dearth of new vehicles, and a likely decrease in the scrapping of older automobiles. In contrast, the need for repair work will increase, though parts requiring steel may become scarce.

OTHER INDUSTRY IMPACTS

Based on the scenario and assumptions discussed, OCIA-NISAC analysts estimated production levels, after the scenario event, for the 6-digit North American Industrial Classification System (NAICS) codes. As an example, NAICS codes 212210 (Iron Ore Mining) and 331110 (Iron and Steel Mills and Ferroalloy Manufacturing) were set to the values found in Tables 3 and 4, respectively, while 336111 (Automobile Manufacturing) and 336112 (Light Truck and Utility Vehicle Manufacturing) were set to 0. The full list of impacted NAICS codes that OCIA-NISAC anticipates will be affected by the disruption scenario can be found in Appendix F.

CONSIDERATIONS REGARDING THE RE-OPENING OF THE POE LOCK AFTER THE CLOSURE SCENARIO

A 6-month closure, from about March 25 to September 25 does not mean that steel production could begin shortly thereafter. First, blast furnaces, which presumably have been hot idled or kept warm during the closure, would have to be re-inspected.[110,111] Extended hot idling can damage or destroy a blast furnace, incurring lengthy repairs times and costs well in excess of $100 million each, though processes have improved that could mitigate

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to the Canadian economy, which is closer to 2 percent. Mexico is the largest exporter of auto parts into North America and should be expected to be impacted by the scenario. See Wall Street Journal, "U.S. Car-Making Boom? Not for Auto-Industry Workers," on March 23, 2015; Canadian Vehicle Manufacturers' Association, "Key Facts" at http://www.cvma.ca/eng/industry/importantfacts.asp, accessed May 6, 2015; U.S. Department of Commerce, "The Automotive Industry in the United States", at http://selectusa.commerce.gov/industry-snapshots/automotive-industry-united-states, accessed May 6, 2015.

109 IHS, Inc., "Average Age of Vehicles on the Road Remains Steady at 11.4 years, According to IHS Automotive," on June 9, 2014 at http://press.ihs.com/press-release/automotive/average-age-vehicles-road-remains-steady-114-years-according-ihs-automotive, accessed April 27, 2015.

110 Blast furnaces generally operate continuously for about 15 years between significant maintenance periods. If a blast furnace is not going to be operated, it must be kept warm by keeping coking coal heated, but not adding in iron ore, limestone and enriched oxygen that make steel. Hot idling, the term to denote this process of keeping the furnace warm is usually not done for periods longer than a few weeks (see Platts, "Platts Steel Glossary," at www.steelbb.com/steelglossary/#term_206, accessed January 17, 2015). Anything longer than a few weeks is considered, herein, to be an extended period.

111 Pittsburgh Business Times, "'Unprecedented' Ice Conditions Cause U.S. Steel Curtailments," on April 4, 2015 at http://www.bizjournals.com/pittsburgh/blog/innovation/2014/04/unprecedented-ice-conditions-cause-u-s-steel.html?page=all, accessed March 29, 2015.

this risk.[112,113,114] A significant problem with hot-idling a blast furnace is the cooling water.[115] Hot idling a blast furnace during the winter may lead to the freezing of the cooling water and damage to the blast furnace.

More problematic than re-starting the blast furnace is restarting the coke batteries. As mentioned in the Background Section, coke batteries concentrate the carbon from coal to make coke, which is an essential ingredient in steelmaking. Industry executives reported that the coke battery must be operated continuously or hot-idled properly to prevent damage. The coke battery is far more likely than the blast furnace to become damaged in this unanticipated outage scenario.

OCIA-NISAC analysts believe that the steel mills will not re-commence mill operations until about mid-December, in order to secure sufficient inventory of iron ore to last through the normal winter closure of the Soo Locks.[116] This assessment is based on the assumption that extending the idling of the steel mills until mid-December would be preferable to a second shutdown due to insufficient iron ore inventory during the normal winter closure. Automotive parts manufacturers could then begin operations in mid-January, but the first cars are not likely to come off production lines until early April.[117,118]

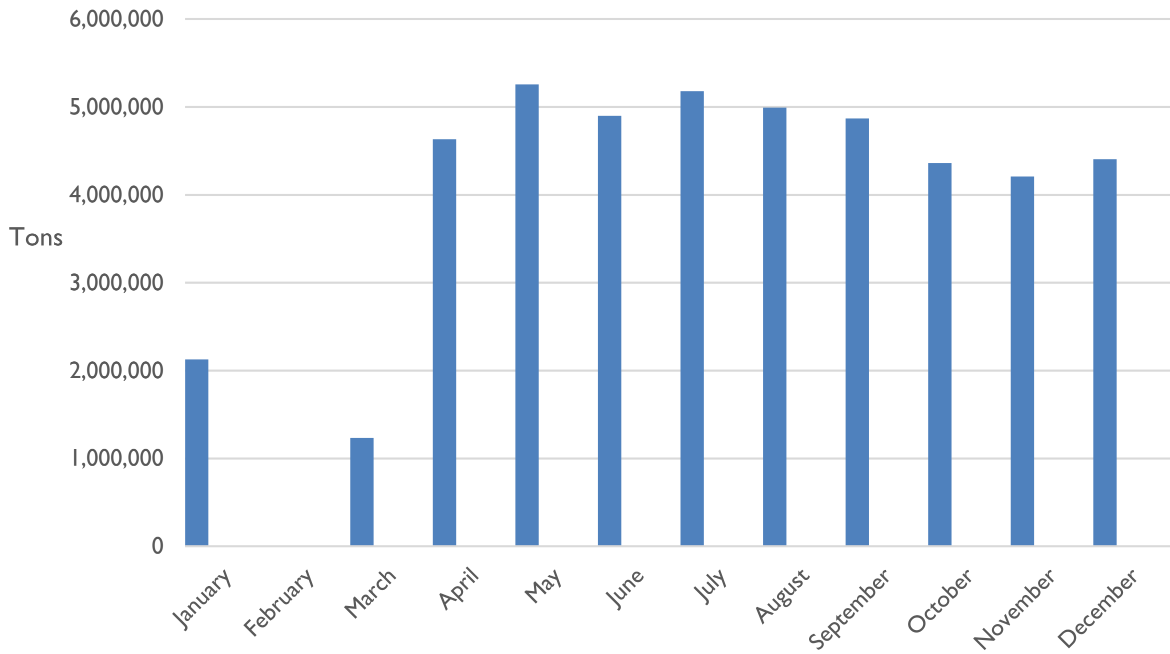

FIGURE 18—AVERAGE MONTHLY SHIPMENT OF IRON ORE OUT OF LAKE SUPERIOR, 2010-2013[119]

Under the scenario, the idled iron ore mines are not likely to restart operations until the first week of December. If the closure were to occur at the start of the navigation season, the iron ore docks along Lake Superior would be at their capacity, around 15 million tons of iron ore. This approximately matches the 15.5 million tons of iron ore that is normally shipped from September 25 through January 15 (the remaining navigation season after the Poe Lock would re-open under this scenario). The average capacity, as seen in Figure 18, should be considered the

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112 Boston Consulting Group, "Flexibility: Streamlining Production," at www.bcgperspectives.com/content/articles/metals_mining_sourcing_procurement_flexibility_innovation_todays_imperatives_steel/?chapter=2, accessed January 15, 2015.
113 Reuters, "Update 2- U.S. Steel CEO says Mulling another Electric Arc Furnace," at http://www.reuters.com/article/2014/03/25/ussteel-furnace-idUSL1N0MM16820140325, accessed January 15, 2015.
114 An industry executive reported the improved processes to OCIA-NISAC.
115 This is also known as 'banking' a blast furnace.
116 An industry executive confirmed this assumption.
117 Industry experts believe that it would take closer to 120 days to have enough supply in the supply lines to start the assembly plants. This would mean that the first cars would not roll off the assembly lines until possibly mid-April.
118 The OCIA-NISAC analysis suggests a similar re-starting date for the appliance, construction, farm, and mining equipment, and railcar manufacturers.
119 Lake Carriers' Association, "Cargo Reports," at http://www.lcaships.com/reports/, accessed May 6, 2015.

maximum capacity because weather plays a significant role in how much product can actually be moved during these 4 months. [120,121] Additionally, inventory levels at the iron ore docks must be near zero on January 15, so that the iron ore mines can extract at their average monthly production levels and have space to store the iron ore. [122] OCIA-NISAC assumes that the first 11 million tons of iron ore shipped through the Poe Lock will be held in storage to get the steel mills through the normal winter closure of the Soo Locks. This leaves about 4.5 million tons of iron ore that could be extracted, pelletized and moved prior to the winter closing of the Soo Locks. The iron mines extract at a rate of about 3.8 million tons per month, meaning that it would take about 5 weeks to produce the 4.5 million tons.

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[120] The average annual shipment of iron ore from Lake Superior through the Soo Locks is about 46.2 million tons.
[121] This is net after taking out shipments from Marquette to Algoma Steel (Essar Steel).
[122] An industry executive reported that the last shipments of the navigation season come out of production, off the railcars, and onto the waiting vessels just before the Soo Locks closes.

POTENTIAL ECONOMIC IMPACTS

The scenario closure would have catastrophic impacts on the regional and National economy. Economic modeling based on the assumptions described in the preceding section shows that approximately $1.1 trillion in economic output, as measured by the Gross Domestic Product (GDP), and over 10.9 million jobs would be lost in the first year following the disruption. The impacts described here are more severe than those predicted in prior studies because this analysis took a comprehensive view of the supply chain and its relationship to the National economy. One previous study of the impacts of a hypothetical closure of the Soo Locks concluded that a 30-day closure would have an economic impact to industry of $160 million.[123,124]

One challenge in properly determining the impact of a supply chain disruption is that each step of the process holds some inventory, even if operating under the "just-in-time" framework.[125] Depending on when a disruption occurs, steel mills would have anywhere from 2 weeks to 3 months of iron ore inventory. Each of the automotive suppliers also holds a certain level of inventory, which may be an additional 2 to 3 weeks. Therefore, a 30-day study would only capture the beginning of the disruption when some steel mills, other automotive tier 1 suppliers and certain automotive lines would only start to face severe shortages.[126]

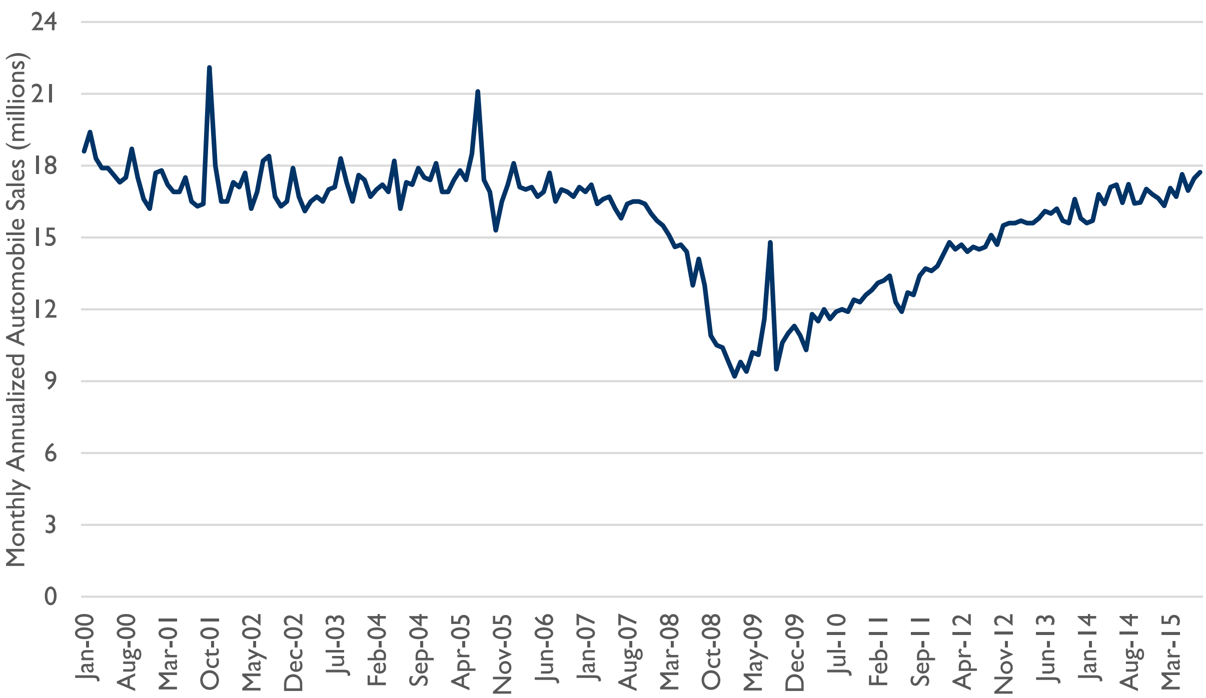

FIGURE 19—ANNUALIZED AUTOMOBILE SALES

A 6-month closure of the Poe Lock, at the start of the navigation season, would be expected to halt all automobile production and the sales of cars manufactured in North America completely for almost 10 months, from about June 1 to April 1. That is, no automobiles would be produced in North America. By comparison, during the 2009 recession, two of the three major automotive companies required bailouts from the United States Government

123 USACE, "Great Lakes Navigation System: Economic Strength to the Nation," on January 2009 at www.lre.usace.army.mil/Portals/69/docs/Navigation/GLN_Strength%20to%20the%20Nation%20Booklet2013v2_final2w.pdf, accessed February 23, 2015.
124 Transport Canada, USACE, US Department of Transportation, The St. Lawrence Seaway Management Corporation, Saint Lawrence Seaway Development Corporation, Environment Canada, US Fish and Wildlife Service, "Great Lakes St. Lawrence Seaway Study," in Fall 2007, at http://www.seaway.dot.gov/publications/great-lakes-st-lawrence-seaway-study-0, accessed January 12, 2015.
125 Just-in-time inventory controls means that each supplier in a supply chain holds only the necessary amount of inventory to maintain operations. This frees up working capital for purposes other than for purchasing inventory.
126 OCIA-NISAC estimates that, based on likely levels of inventory held throughout the supply chain, catastrophic failure would likely occur around 42 days after a closure of the Poe Lock. This estimate has not been reviewed by any industry executives.

when annualized sales of new automobiles had dropped from the typical 16–18 million units to about 9 million units (see Figure 19).[127]

Initial conversations with the automotive industry confirm that the loss of Great Lakes steel would be catastrophic to the industry. Industry officials reported that:

- "The loss of the integrated mill steel supply for 180 days would be catastrophic to the North American Auto Industry including its tier one suppliers…There is no contingency plan, stockpile or off shore sourcing action that could come close to mitigating the situation."
- "[The Firm] does not have long-term contingency plans for a disruption in normal steel supply. We have limited ability to purchase small amounts of some types of steel on the open market, but it would be unlikely to support full production of all required parts for even a single product line."
- "There are no contingency plans in place to respond to a disruption of normal steel supplies."

UNEMPLOYMENT IMPACTS

In support of OCIA-NISAC, Sandia National Laboratories used the Regional Economic Models, Inc. (REMI) model to estimate the impacts of an unanticipated Poe Lock closure on economic productivity and employment.[128] Analysts conducted the REMI analysis in two steps: first, a baseline forecast was computed, in which there was no change to the economy; and second, an alternative forecast was generated, in which a set of simulation variables model a change in the economy. For the Poe Lock scenario, the assumptions described in the prior section of this report, and, in detail, in Appendix F, with respect to the disruptions to the iron mining, steel production, automotive manufacturing industries, and other industries, formed the parameters for the simulation.

At the National level, the model predicts that the Poe Lock closure scenario would add 5.8 percentage points to the unemployment rate, currently at 5.5 percent.[129] This would bring the National unemployment rate under the closure scenario to 11.3 percent. This would exceed the highest level of National unemployment recorded during the 2008-2009 recession, which peaked at 10.0 percent in October 2009.[130]

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127 Federal Reserve Bank of St. Louis, "Light Weight Vehicle Sales: Autos & Light Trucks," on June 28, 2015 at research.stlouisfed.org/fred2/series/ALTSALES/, accessed June 28, 2015.

128 Regional Economic Models, Inc. The REMI model is a commercially available dynamic economic forecasting model, and incorporates region-specific descriptions of inter-industry relationships. As a result, the model captures the industry structure of a particular region, as well as transactions between industries. For more information, see REMI Web page, "The REMI Model," 2015, at www.remi.com/the-remi-model, accessed May 18, 2015.

129 Bureau of Labor Statistics, "The Employment Situation -- May 2015," on June 5, 2015 at http://www.bls.gov/news.release/empsit.nr0.htm, accessed June 11, 2015.

130 Bureau of Labor Statistics, "Labor Force Statistics from the Current Population Survey," at http://data.bls.gov/timeseries/LNS14000000, accessed June 11, 2015.

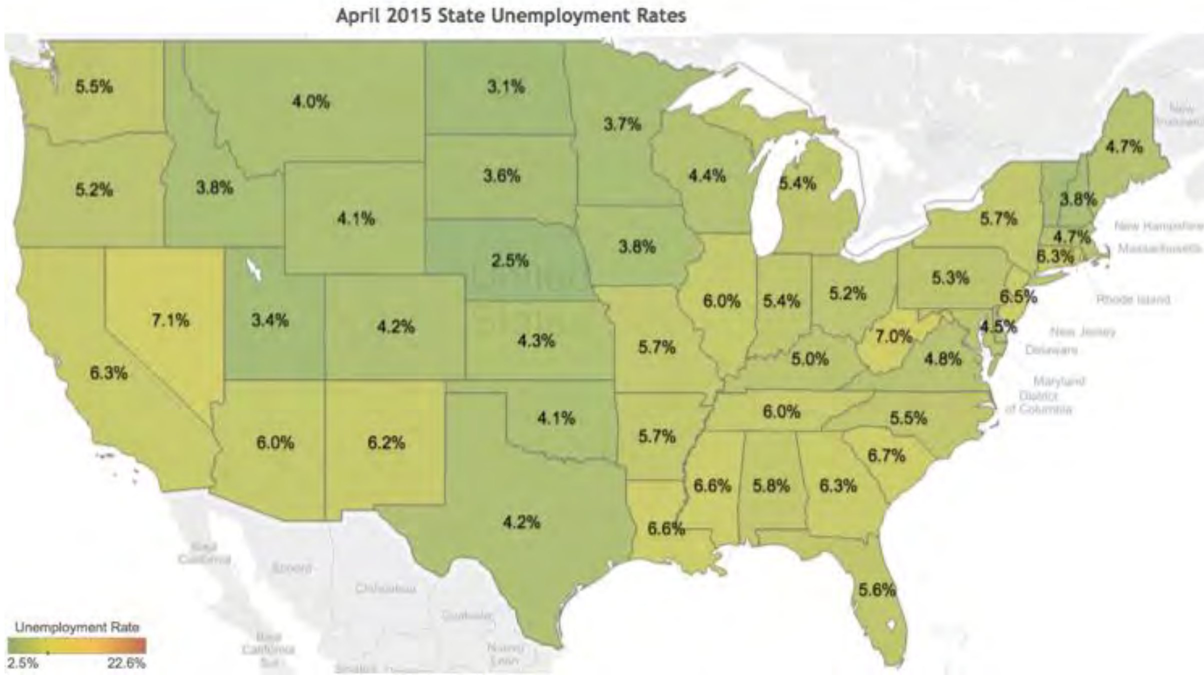

FIGURE 20—APRIL 2015 STATE UNEMPLOYMENT RATES[131]

Figure 20 displays State-level unemployment rates for April 2015 (the most recent available), as determined by the U.S. Department of Labor's Bureau of Labor Statistics. Nebraska has the lowest unemployment rate at 2.5 percent and Nevada has the highest at 7.1 percent. Figure 20 is used as the baseline with the unemployment impacts from the Poe Lock closure scenario added to this baseline.

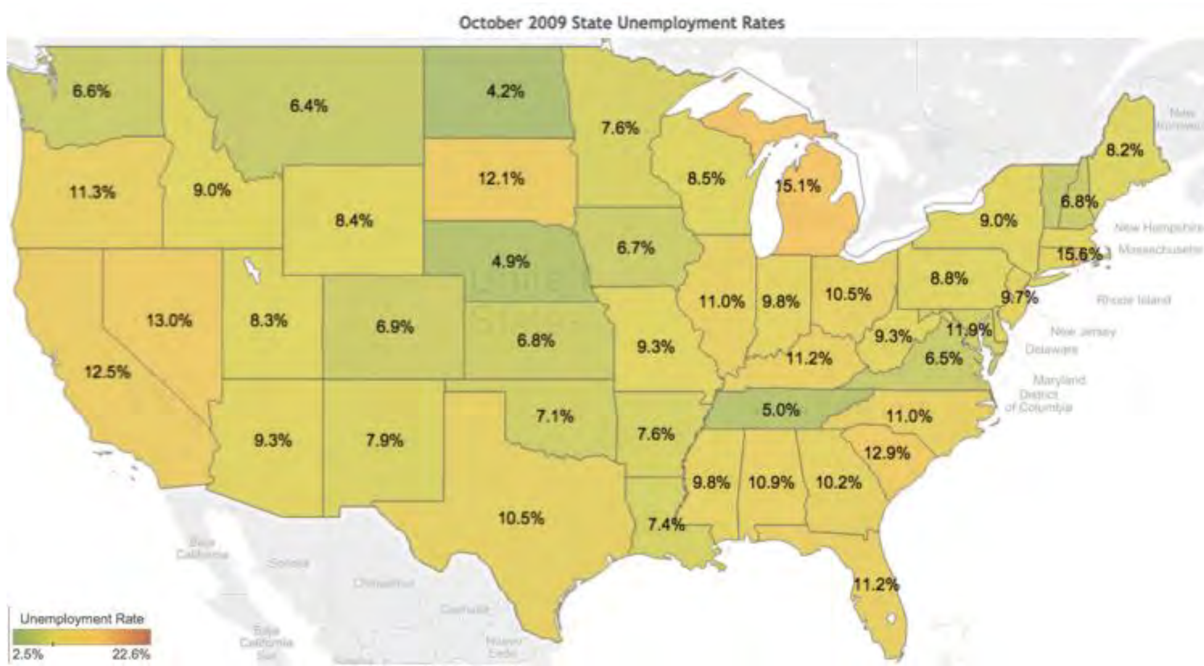

FIGURE 21—OCTOBER 2009 STATE UNEMPLOYMENT RATES[132]

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[131] Bureau of Labor Statistics, "Unemployment Rates for States," on May 27, 2015 at http://www.bls.gov/web/laus/laumstrk.htm, accessed May 31, 2015.

For perspective, Figure 21 shows unemployment levels from the height of the 2008–2009 recession. At its peak in October 2009, unemployment was high across the Nation, particularly in California and Nevada in the west, South Dakota and Michigan in the Midwest and north, and Rhode Island in the east. The color scale is the same for Figures 20 and 21: green represents the lowest level of unemployment (generally below 7 percent), and yellow and orange represent the highest levels of unemployment experienced during the 2009 recession. North Dakota had the lowest unemployment rate at 4.2 percent and Rhode Island had the highest at 15.6 percent.

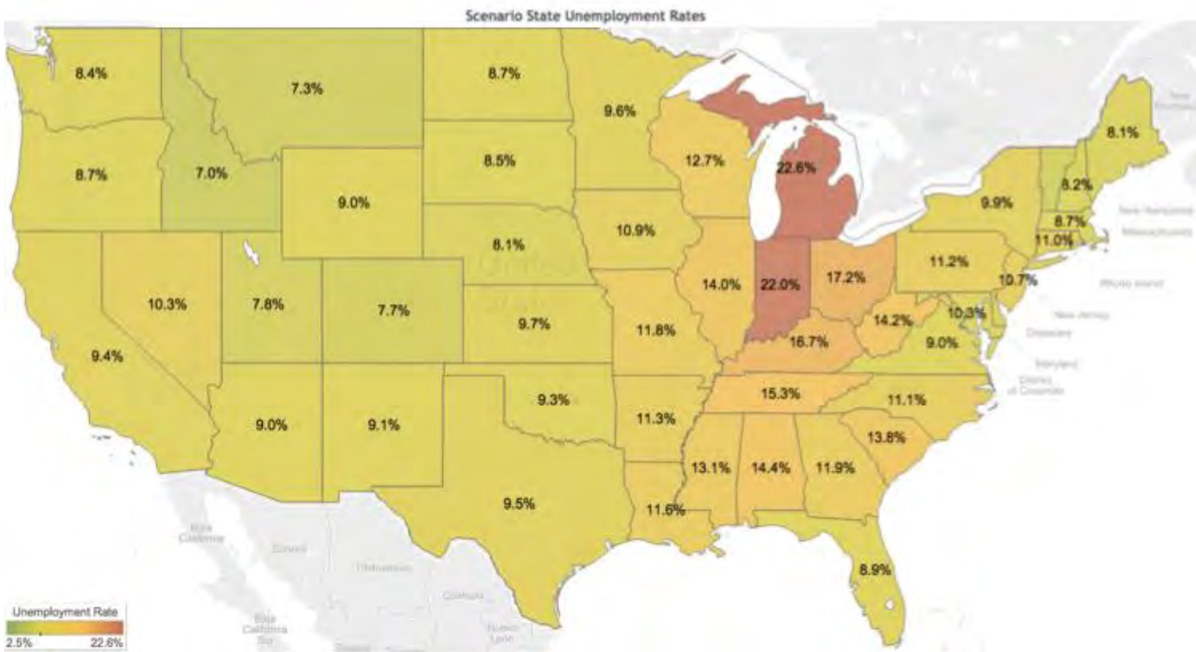

FIGURE 22—POE LOCK CLOSURE SCENARIO STATE UNEMPLOYMENT RATES

Economic modeling suggests that the Poe Lock closure scenario would result in 10.9 million people out of work in the United States, with additional losses in Canada and Mexico.[133] Figure 22 displays the potential State-level unemployment rates under the Poe Lock closure scenario. The Figure reflects changes in unemployment due to the Poe Lock closure (see Figure 23) overlaid on the baseline unemployment rates found in Figure 20. The color scale in Figure 22 remains consistent with that in Figures 20 and 21, so that green represents the lowest level of unemployment (generally below 7 percent); yellow and orange represent the highest levels of unemployment experienced during the 2009 recession; and red the highest levels of unemployment, which occurs under the closure scenario. Under the Poe Lock closure scenario, exceptionally high rates of unemployment occur along the Great Lakes and south. Unemployment rates in Indiana and Michigan would reach or exceed 22 percent and all of the Great Lakes States, except for Minnesota and New York, have unemployment rates that would exceed 10 percent.

[132] U.S. Bureau of Labor Statistics, "Local Area Unemployment Statistics for October 2009, on December 19, 2014 at http://www.bls.gov/web/laus/laumstrk.htm, accessed January 2, 2015.
[133] The lost economic output would be mitigated by government policy responses, both automatic (e.g., unemployment insurance) and considered. The Regional Economic Models, Inc. (REMI Model) used to estimate the economic impacts did not consider consumer response to this type of event (e.g., purchase a vehicle from an off-shore manufacturer [most foreign cars in the United States are made domestically], buy a used car, or maintain the existing car), employment losses at new car dealerships, and impacts to other industries (e.g., railcar and locomotive manufacturing).

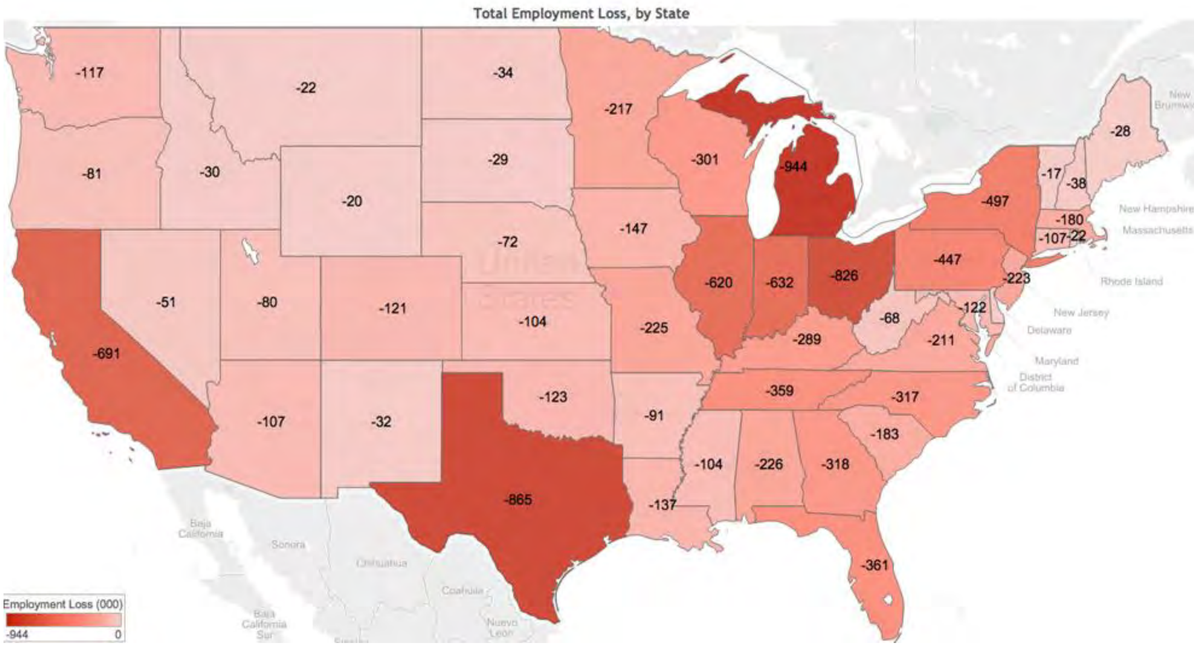

FIGURE 23—POE LOCK CLOSURE SCENARIO, STATE EMPLOYMENT CHANGES

Three States (Michigan, Texas, and Ohio) would experience job losses in excess of 800,000 people due to an unanticipated closure of the Poe Lock (see Figure 23). Another four States (California, Indiana, Illinois, and New York) would experience job losses that about equal or exceed 500,000 people due to the closure. Job losses in the Mountain States and Northern Plains would be relatively small, as there are few automobile assembly plants in these areas (see Figure 17).

Table 6 compares the unemployment rates of the six most affected States to that which occurred in October 2009. In every case, the State unemployment rate is projected to be higher than it was during the 2008-2009 recession; in most cases, the expected unemployment rate would be substantially higher.

TABLE 6—COMPARISON OF UNEMPLOYMENT RATES BETWEEN 2009 AND CLOSURE SCENARIO FOR SELECTED STATES

State	October 2009 Unemployment Rate	Closure Scenario Unemployment Rate
Alabama	7.4%	14.4%
Indiana	9.8%	22.0%
Kentucky	11.2%	16.7%
Michigan	15.1%	22.6%
Ohio	10.5%	17.2%
Tennessee	5.0%	15.3%

The ability to recover after the 6-month scenario closure may be predicated on the skilled labor remaining in the affected area. Many of the jobs associated with the iron mining - integrated steel production - manufacturing supply chain require highly skilled labor. If, over the course of the 6-10 month disruption, these people move elsewhere, the labor needed to mine, mill, or manufacture the output may not be available. Hiring and training new labor will take a significant investment and may significantly delay restarting production. These considerations have not been included in the model as the movement of labor is speculative.

ECONOMIC OUTPUT IMPACTS

The decrease in GDP attributable to a Poe Locks closure scenario is expected to be about $1.1 trillion, which is roughly a 6-percent decrease. Although not directly comparable, it may be useful to recall that during the worst six month period during the 2008-2009 recession, the GDP fell at a 7 percent annualized rate.[134,135] The National GDP growth rate since the first quarter of 2009 has been approximately 2.2 percent, per year.[136] This would suggest, that if the U.S. continues this rate of expansion, the annualized decease in the GDP after the closure scenario would be approximately 4 percent for the full year.[137]

A recession brought about by an unexpected closure of the Poe Lock would be categorically different from historical recessions. Recessions are usually caused by falling aggregate demand, credit contractions, or oil supply shocks, for which government fiscal or monetary policy can mitigate the length or severity of the recession. A supply shock as contemplated herein may be unprecedented. The closest example may be recession following the 1973-1974 Arab Oil Embargo. In that case, however, oil was available in the United States, but not in sufficient supply to meet demand. The dust bowl in the 1930s resulted in a lack of arable land in the Midwest, which led to the largest population migration in the United States.[138] In the Poe Lock closure scenario, there is no plan, policy, or remedy that could restart automobile production. Government policy would be generally limited to transfer payments to those individuals directly impacted by the event.

Given the size of the economic impact, it is illustrative to consider the economic value of a single Laker trip. A 1000-footer, carrying a cargo of 70,000 short tons, has a commodity replacement value of about $4.0 million. The iron ore grade shipped on the Great Lakes has a per ton value of about $57 multiplied by the 70,000 tons.[139] The REMI GDP estimate of a $1.1 trillion impact is based on the inability to ship 46.2 million tons of iron ore, which is the four-year average from 2010-2013. This suggests that, in the closure scenario, each ton of iron ore contributes about $23,800 of economic value; a Laker carrying 70,000 tons represents a loss of $1.7 billion to the U.S. economy and potentially another $340 million to the Canadian and Mexican economies.[140,141]

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134 Federal Reserve Bank of St. Louis, "Real Gross Domestic Product" at https://research.stlouisfed.org/fred2/series/GDPC1#, accessed June 11, 2015.

135 There are a number of factors that make the GDP numbers not comparable. For instance, the Poe Lock closure scenario does not account for transfer payments and government policy responses that could lessen the GDP impacts.

136 Federal Reserve Bank of St. Louis, "Real Gross Domestic Product" at https://research.stlouisfed.org/fred2/series/GDPC1#, accessed June 11, 2015.

137 This is estimated by subtracting the 6 percentage point loss from the estimated 2.2 percent increase.

138 Public Broadcasting Service, "American Experience: Mass Exodus from the Plains", at http://www.pbs.org/wgbh/americanexperience/features/general-article/dustbowl-mass-exodus-plains/, accessed April 22, 2015.

139 Bloomberg Business, "Iron Ore Price Outlook Cut by World Bank as Supplies to Expand" on April 22, 2015 at http://www.bloomberg.com/news/articles/2015-04-22/iron-ore-price-outlook-cut-by-world-bank-as-supplies-to-expand, accessed May 6, 2015.

140 The term 'economic value' is not the same as profits. The concept here is that automobile lines shut down due to the lack of a single part. If the iron ore is not shipped through the Poe Lock, automotive steel cannot be made, and therefore, an automobile cannot be assembled. For this illustrative purpose, OCIA-NISAC is attributing the total value added in the supply chain to the iron ore shipments.

141 OCIA-NISAC reviewed the significant commodity groups transporting goods on the U.S. waterways (USACE, "Waterborne Commerce of the United States: Calendar Year 2012," at http://www.navigationdatacenter.us/wcsc/pdf/wcusnatl12.pdf, accessed May 6, 2015). Petroleum is the largest group, with about 41 percent of all commerce, but most of this group represents crude oil imported into the Gulf Coast. The second largest group is coal. An article prepared for The Center for Energy and Economic Development, Inc. by Pennsylvania State University (Rose, Adam and Dan Wei, "The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015," in July 2006) estimated that coal will contribute $1 trillion to the U.S. economy. Assuming that this estimate is accurate and further assuming that all coal, at some point, is shipped on the waterways and captured by the USACE data, then the per ton contribution to the U.S. economy is slightly over $3000 per ton, or less than a quarter of the per ton contribution of iron ore. Further, there are both transportation alternatives to moving coal on the waterway, the use of the more expensive rail routes, and alternative fuel sources for electric power generation, the use of natural gas. The other major product categories moving on the waterways are: Crude Materials (e.g., limestone, sand, wood), Food and Farm Products, and Chemical and Related Products). Most of these products are either low value, abundant in multiple locations throughout North America, are for export and therefore do not have an additional multiplier effect within North America, or has multiple alternative sources of transportation (e.g., rail, truck). Manufactured equipment, which may constitute the highest valued products moving on the waterways, are made up of machinery, vehicles, and electrical machinery, which, in most cases, uses iron ore as the first stage of development.

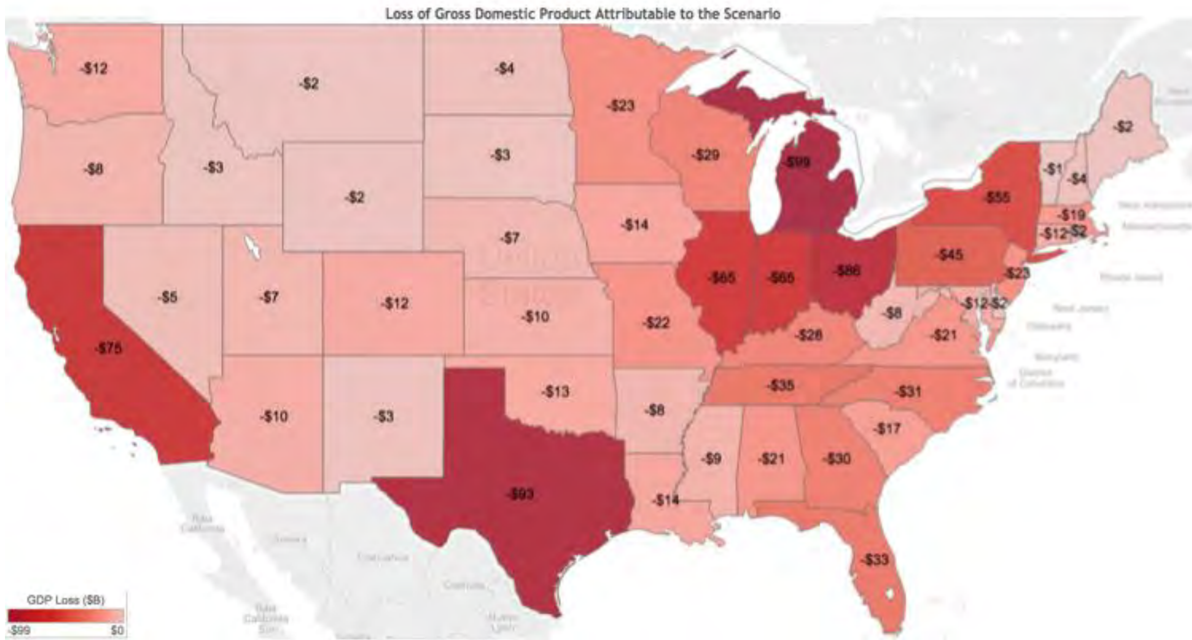

FIGURE 24—POE LOCK CLOSURE SCENARIO GROSS DOMESTIC PRODUCT CHANGES

The closure scenario could cost Michigan and Texas close to $100 billion of GDP each (see Figure 24).[142] Another five States (California, Illinois, Indiana, New York and Ohio) could lose between $55 billion - $86 billion in GDP each. Together, these seven States account for about 50 percent of the total GDP loss caused by the scenario disruption.

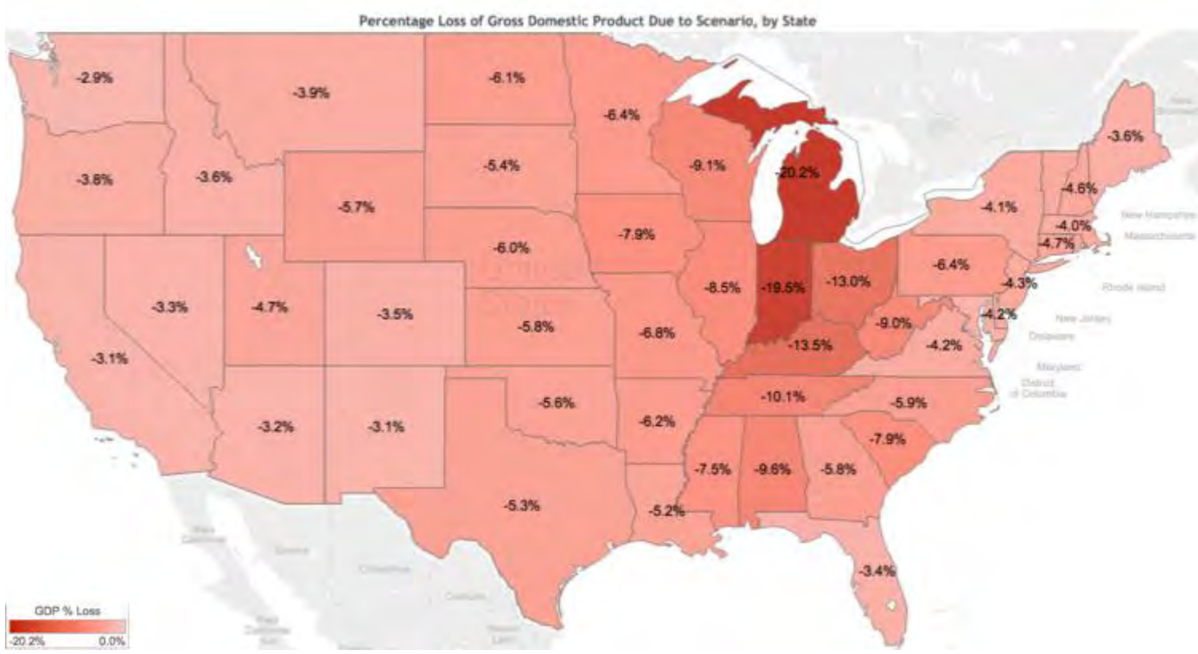

FIGURE 25—POE LOCK CLOSURE SCENARIO, GROSS DOMESTIC PRODUCT PERCENTAGE CHANGE

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142 Technically, the economic output at the State level is measured as the Gross State Product. For simplicity sake, we refer to the State-level economic output as GDP with the meaning of the State's contribution to the National GDP.

Figure 25 shows the estimated percentage change in GDP, by State. Michigan and Indiana would feel the most severe impacts, as their economies could lose approximately 20 percent of economic activity. Economic activity in Kentucky, Ohio, and Tennessee could contract between 10 and 13 percent, each. Another three States, Alabama, West Virginia, and Wisconsin could each lose about 9 percent of economic activity due to the scenario closure. The States just to the east of the Mississippi River would contract more than the States just to the west of the Mississippi River or in the Southeast. The Western States would contract by about 3 percent, which depending on their growth rates at the time of the scenario closure, could mean that they continue to grow, though at a slower rate. As an example, Colorado grew at a 4.7 percent rate in 2014, and the scenario closure results projects a 3.5 percent decrease in economic activity. [143] Colorado would still grow at a better than 1 percent rate for the year of the closure. New England and the Mid-Atlantic States would see contractions in the 4 to 6 percent range.

[143] Bureau of Economic Analysis, "Percent Change in Real GDP by State, 2014," on June 10, 2015 at https://www.bea.gov/newsreleases/regional/gdp_state/gsp_newsrelease.htm, accessed June 12, 2015.

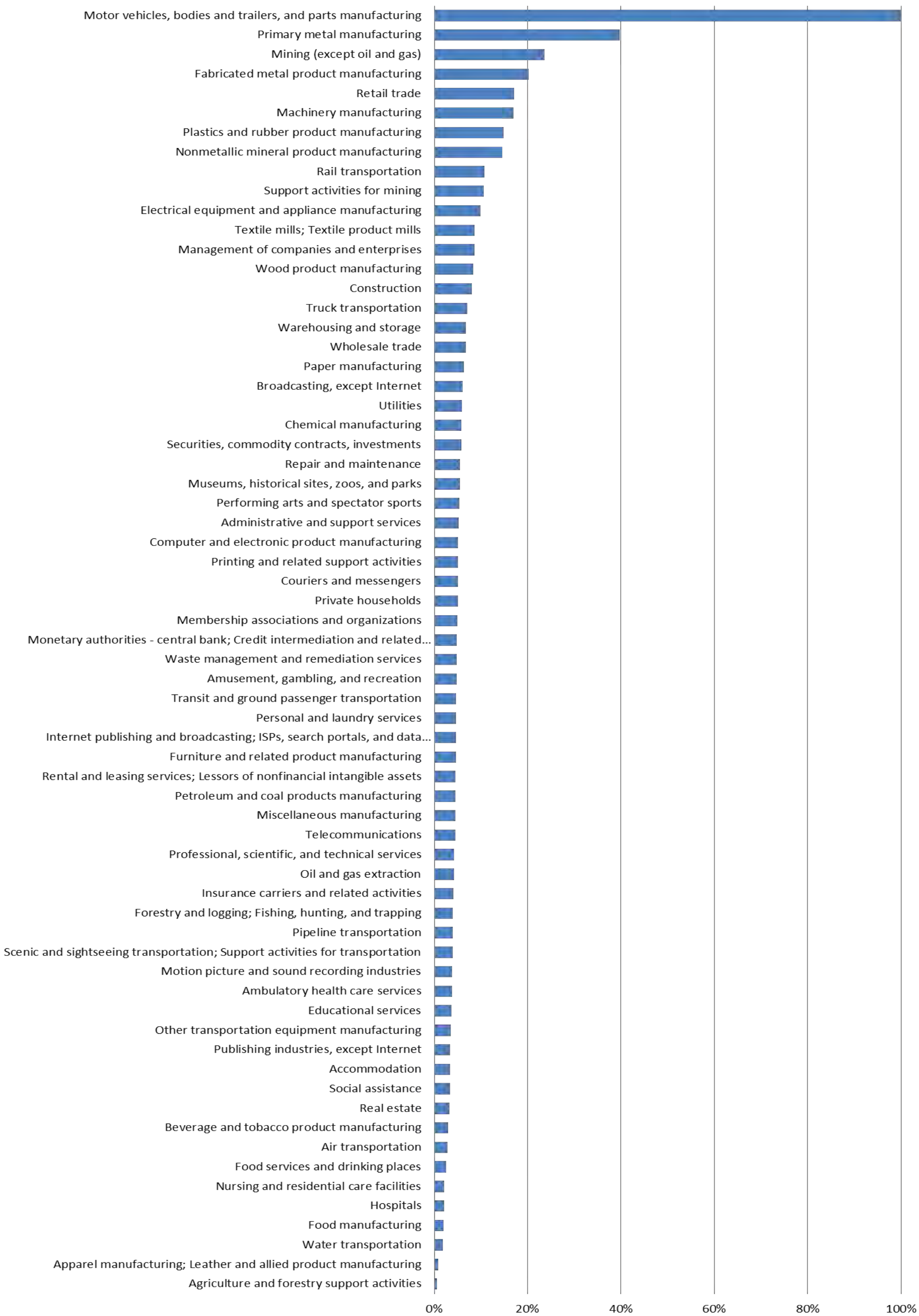

FIGURE 26—GDP PERCENT CHANGE, BY INDUSTRY

The industry category most impacted by the Poe Lock closure scenario is motor vehicles, bodies and trailers, and parts manufacturing industry (see Figure 26). This was not surprising, as this parameter in the model represented the system shock from the Poe Lock closure scenario. Analysts programmed the motor vehicles category to contract by 100 percent, in order to represent the cessation of automobile manufacturing under the scenario, for all of the reasons described in the Assumptions sections. Primary metal manufacturing (which captures the contraction in the integrated steel industry), mining (which captures the contraction in the iron ore mining), and fabricated metal manufacturing all are anticipated to contract between 20 and 40 percent, respectively. Retail trade, which captures, among other direct and indirect effects, new car sales, is anticipated to contract by about 17 percent.

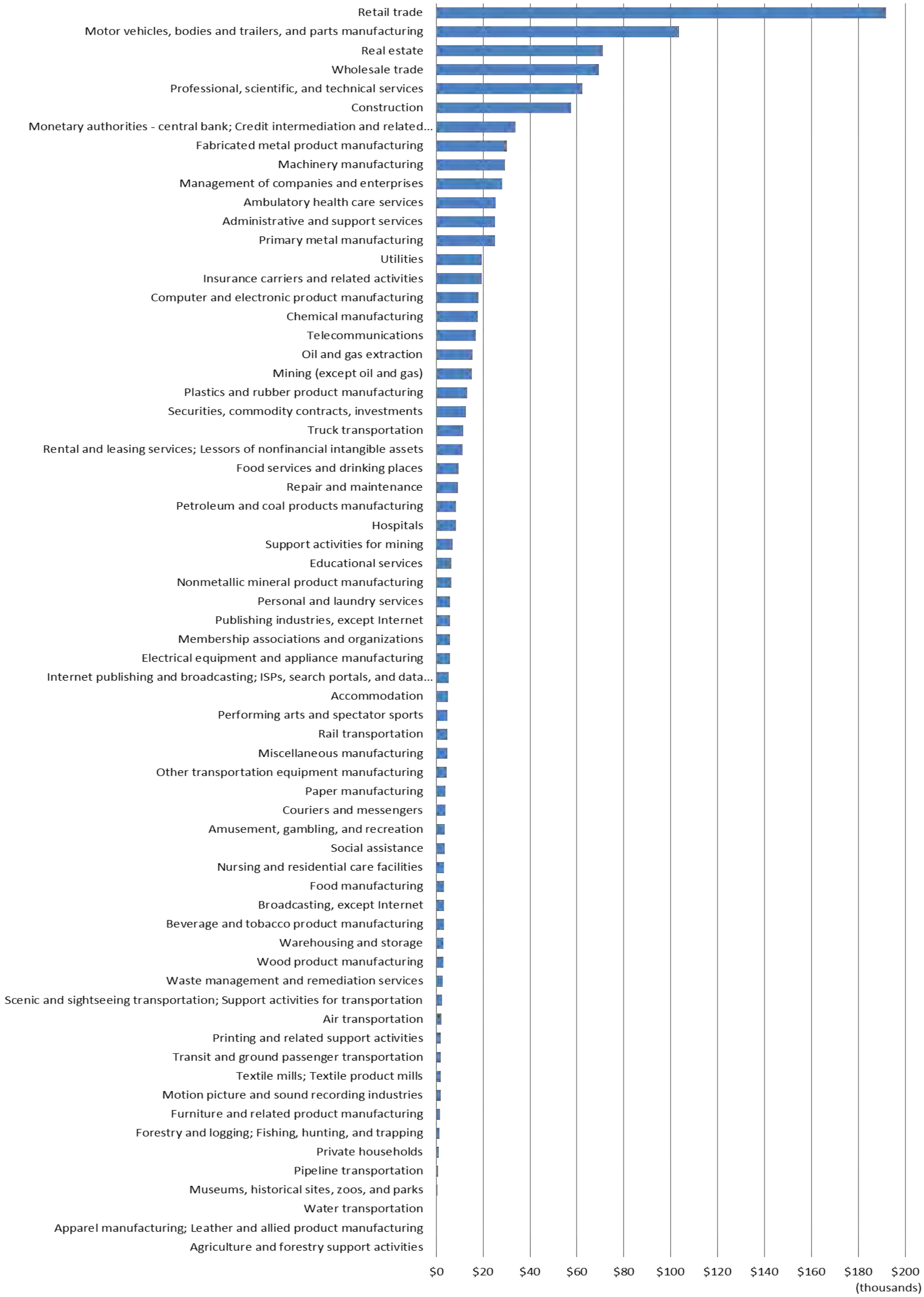

FIGURE 27—DECREASE IN GDP, BY INDUSTRY

In absolute terms, the retail trade industry sector is the most affected by the closure scenario (see Figure 27). The REMI model predicts a $192 billion contraction, primarily due to a lack of new cars to sell. The number also includes a decrease in appliance and auto part sales. Real estate and construction, combined, would be the second largest impact at a $129 billion contraction. This is mainly a second-order effect reflecting decreased demand. The contraction in the motor vehicles, bodies and trailers, and parts manufacturing industry is roughly $103 billion.

ALTERNATIVE STRATEGIES CONSIDERED

The serious impacts of this scenario are due to the history of the iron mining - integrated steel production - manufacturing supply chain, which has evolved over the last 160 years to maximize efficiency. The resulting system has permitted these industries to survive in increasingly competitive markets, but has fostered neither resilience nor flexibility. In the event of an unanticipated 6-month closure, most steel mills, including the steel mills most critical to significant aspects of the Nation's economy, would have no way to receive iron ore.

OCIA-NISAC assessed a number of possible mitigation strategies, including:

- Moving iron ore by rail,
- Moving iron ore by truck,
- Shipping from the Port of Escanaba, Michigan,
- Lightering on smaller Lakers which can transit the MacArthur Lock,
- Obtaining steel or iron ore from foreign sources,
- Stockpiling ore at the steel mills, and
- Switching automotive production to use aluminum for some parts.

None of these strategies employed singly would significantly alleviate the issues. Even if a mitigation strategy is identified and employed, any option would increase cost and decrease competitiveness for the firms involved.

MOVING IRON ORE BY RAIL

Moving iron ore from the mines to the mills is not a viable mitigation; as one industry executive put it, "it's not even in the realm of the possible; it's just not going to happen." Even if the steel mills could accept iron ore from rail transportation, congested rail lines and the lack of equipment would make the use of rail impractical.

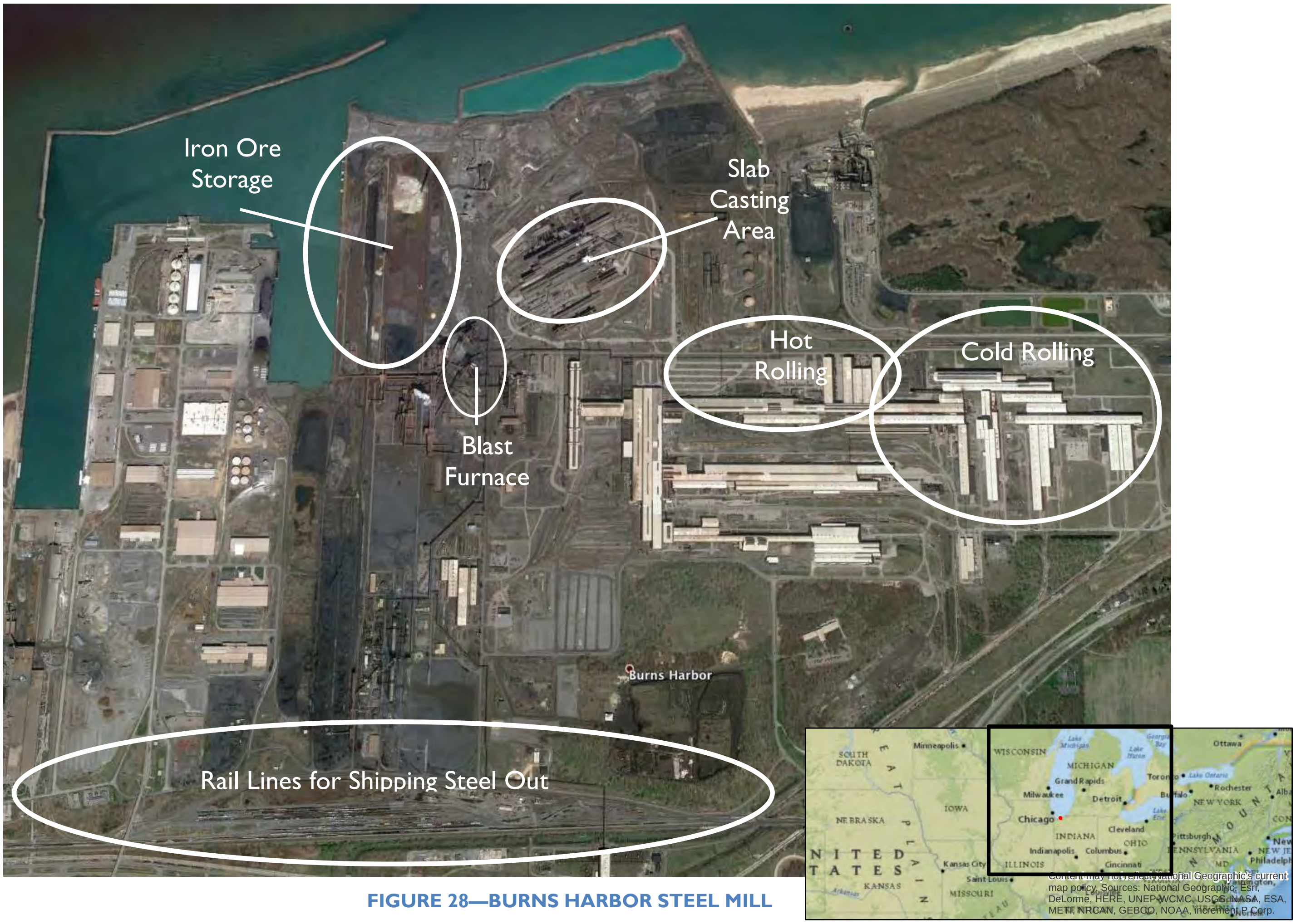

FIGURE 28—BURNS HARBOR STEEL MILL

For 160 years, the steel mills along the Great Lakes have received their iron ore via Lake Carrier; the mills are designed to receive iron ore by water and there is logistically no way to receive iron ore by rail.[144,145] One steel mill, Lake Erie Works (U.S. Steel) does not have a rail line at its mill; other steel mills such as Indiana Harbor (ArcelorMittal) and Burns Harbor (ArcelorMittal) do not have the infrastructure to receive iron ore by rail; while another steel mill, Great Lakes Works (U.S. Steel) on Zug Island, could potentially receive iron ore by rail for one of its two blast furnaces.[146] As shown in Figure 28, the Great Lakes steel mills are built with the iron ore inventory facing the water and the rail lines on the other side of the mills inland for truck or rail shipment of steel out. Figure 28 is an image of Burns Harbor, but it is representative of the majority of Great Lakes steel mills.

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[144] The mill, now called Indiana Harbor (ArcelorMittal), was built in 1901, while Gary Works (U.S. Steel) was built in 1906 (Encyclopedia of Chicago, "Iron and Steel" at www.encyclopedia.chicagohistory.org/pages/653.html, accessed January 2, 2015.) However, prior to their development, earlier Great Lakes steel mills have been receiving iron ore by barge since 1855 (Michigan State University, "Iron Ore/Taconite Shipping," at http://web2.geo.msu.edu/geogmich/iron_ore__taconite.html, accessed January 2, 2015.)

[145] Industry officials indicated that Gary Works (U.S. Steel) has the ability to take in 1-2 unit trains per week, and did do so up until 5 - 10 years ago, until Chicago became too congested (see next page). However, 2 trains per week would only provide about 1/8th of Gary Works' iron ore requirements.

[146] Technically, Great Lakes Works was a peninsula that Henry Ford or Samuel Zug converted into an island (Crains Detroit, "Beyond the Shores," on August 19, 2012 at www.crainsdetroit.com/article/20120819/FREE01/308199988/beyond-the-shores, accessed January 2, 2015.

NORTH AMERICAN RAIL CARRIERS

In the United States, the vast majority of rail shipment is provided by the Class I railroads. The North American Class I freight railroads are Burlington Northern and Santa Fe Railway (BNSF), Canadian National Railway (CN), Canadian Pacific Railway, CSX Transportation (CSX), Kansas City Southern Railway, Norfolk Southern Railway (NS) and the Union Pacific Railroad. BNSF and CN are the primary rail companies operating within Minnesota and Michigan and between Minnesota, Michigan, and Chicago. Chicago is the central rail point in the United States. CN, CSX, and NS are the primary carriers of products, equipment and supplies, from Chicago east to the steel mills.

There are an insufficient number of locomotives and railcars to move the iron ore, even if the steel mills could receive iron ore by rail. A 2012 Sandia National Laboratories study for OCIA-NISAC estimated that 1670 railcars per day would be necessary to move the iron ore, while an industry expert believed that 2500 railcars per day would be necessary.[147] This number of railcars and the locomotives are not believed to exist.[148] The current supply of rail cars that could carry iron ore "would perhaps be best described as zero to extremely limited."[149] Further, "there are many additional potential constraints that must be taken into account in assessing capacity. This includes hiring and training personnel to operate the trains, locomotive supply, and additional yard tracks to land the trains and fuel the locomotives."[150]

The Northern and Midwest States already face heavy rail congestion, due in part to the movement of Bakken shale oil by rail, which would preclude any large-scale movement of iron ore by rail.[151] Industry executives have also indicated that some of the congestion is due to issues on other North American rail lines, which has forced the traffic onto the lines that would be needed to move iron ore. OCIA-NISAC estimates that the volume of railcars between Duluth, MN and Minneapolis/St. Paul would increase by 200 percent, from Minneapolis/St. Paul to Milwaukee would increase by about 40 percent, and the Milwaukee to Chicago lines would face volume increases of over 35 percent.[152] One industry executive stated that the infrastructure does not exist "to support the level of traffic [conceived under the disruption scenario] without major investment in infrastructure and the time to construct." This industry executive speculated that, at most, one to two unit trains a week could move from Minnesota to the steel mills, assuming that Bakken Crude movements do not increase.[153] This would not come close to the 20 unit trains per day that would be required to move sufficient quantities of iron ore from Minnesota and Michigan to the Great Lakes steel mills.[154]

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147 OCIA-NISAC, "Modeling the Impacts of a Prolonged Closure of the Soo Locks: Phase I," February 2012.
148 Further, the railcars used to move the iron ore must be able to transport iron ore. Only standard gondolas, without rotary coupling systems used to dump coal quickly, can be used to move iron ore. The mass of the iron ore can damage other types of rail cars. The standard gondolas can only be filled about 1/3rd full before it reaches its weight limits.
149 Email from industry executive.
150 Email from industry executive.
151 MPR News, "Solution to Congested Rail Lines May be Years Away," September 30, 2014 at www.mprnews.org/story/2014/09/30/unclogging-rail-traffic, accessed January 3, 2015.
152 OCIA-NISAC, "Modeling the Impacts of a Prolonged Closure of the Soo Locks: Phase I," February 2012.
153 The Bakken shale oil trains do not share rail cars or facilities with the iron ore trade.
154 Bakken Crude is the oil play located in North Dakota and Montana. 700 railcars a day are traveling from North Dakota, through Minnesota and Wisconsin, to Chicago, up from close to 0 in 2011.

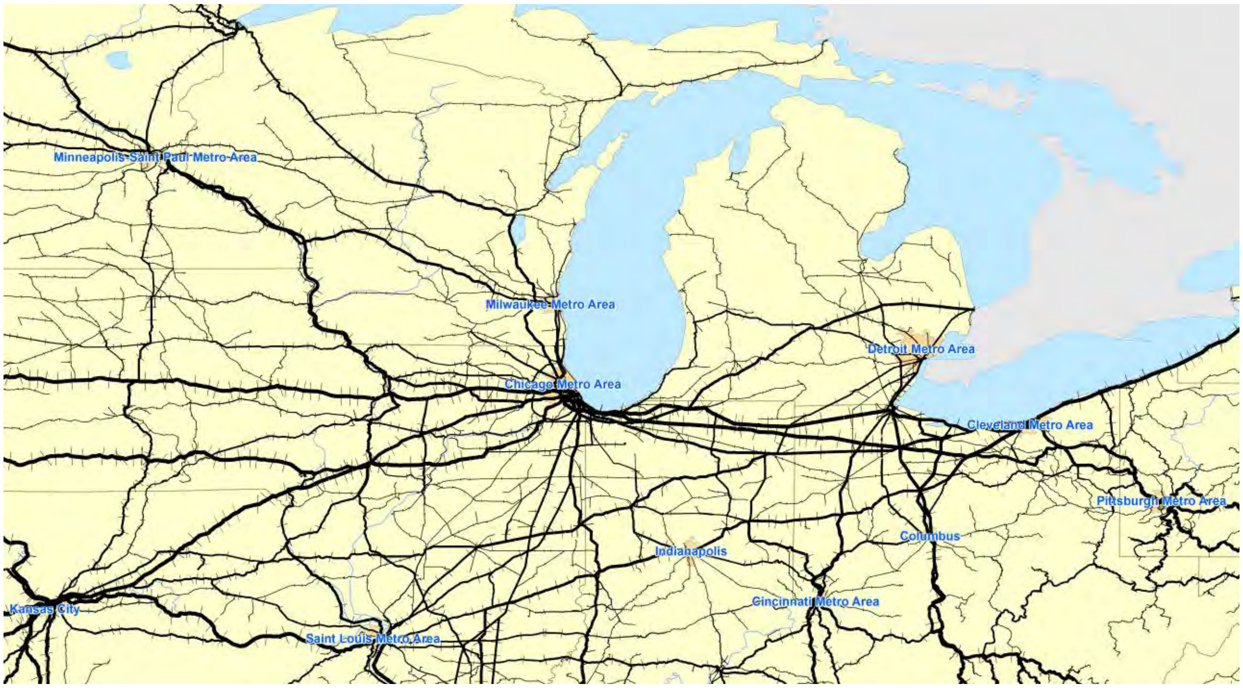

FIGURE 29—MAP OF MIDWEST RAIL LINES, THICKNESS OF LINE REPRESENTS DENSITY OF USE[155]

Moreover, any increase in rail traffic would be on some of the most heavily congested rail lines in the Nation (see Figure 29). Chicago, through which a quarter of all freight rail traffic in the Nation passes, is the most congested area in the Nation; shippers report that they can move goods two-thirds the way from Chicago to Los Angeles in the time it takes to traverse Chicago.[156] The three largest steel mills in the Nation are located about 25 miles southeast of Chicago within 10 miles of Gary, Indiana.

Some commodity types such as coal, iron ore, intermodal containers, and motor vehicles, are not required to pass through rail yards *en route* to their destination—they are allowed to bypass the rail yards by means of bypass rail links. These types of commodities are moved in "unit trains," which move directly from an origin to a destination because there is sufficient volume between the specific origin and destination to support an entire train. Because of this, the travel times of these shipments may be less affected by rail yard congestion, though they still must travel on congested railways, enter rail yards for inspection and maintenance, and not all rail yards have bypass rail links. Most unit trains designed to carry iron ore would be unloaded and returned to their origination point empty because the commodities tend to flow in one direction.

The existing congestion is such that, in 2014, utilities and grain producers petitioned the U.S. Government to impose a timetable on BNSF to alleviate the difficulties.[157] The Surface Transportation Board of the Department of Transportation (DOT) issued a decision that BNSF was "to publicly file their plans to timely resolve their backlog of grain car orders, as well as weekly status reports pertaining to grain car service."[158] Cliffs Natural Resources, the leading iron ore mining company, reported on October 10, 2014, "that due to ongoing insufficient rail service [Cliffs] will immediately begin utilizing trucks to transport iron ore pellets [the 82 miles] to the Duluth-Superior Harbor."[159] However, since that time, Cliffs has returned to rail for this leg of transportation.

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155 DOT/Federal Railroad Administration, "Freight Rail Today," at http://www.fra.dot.gov/Page/P0362, accessed February 4, 2015.
156 New York Times, "Freight Train Late? Blame Chicago," at http://www.nytimes.com/2012/05/08/us/chicago-train-congestion-slows-whole-country.html?_r=0, accessed February 4, 2015. The article further stated that some trains go across Chicago at "about a quarter the pace of many electric wheelchairs." This description was confirmed by industry executives.
157 Wall Street Journal, "Utilities Press Railroad to Speed Coal Deliveries," on November 23, 2014 at www.wsj.com/articles/utilities-press-railroad-to-speed-coal-deliveries-1416786948?cb=logged0.04710544156841934, accessed January 3, 2015.
158 Surface Transportation Board, "Docket No. EP 724 (Sub-No. 2) United States Rail Service Issues-Grain," on June 20, 2014 at www.stb.dot.gov/decisions/readingroom.nsf/UNID/F8F5F23979674DB485257CFD007024F0/$file/43842.pdf, accessed January 3, 2015.
159 Cliffs Natural Resources, "News Release: Hibbing Taconite Begins Transporting Iron Ore Pellets by Truck," on October 10, 2014.

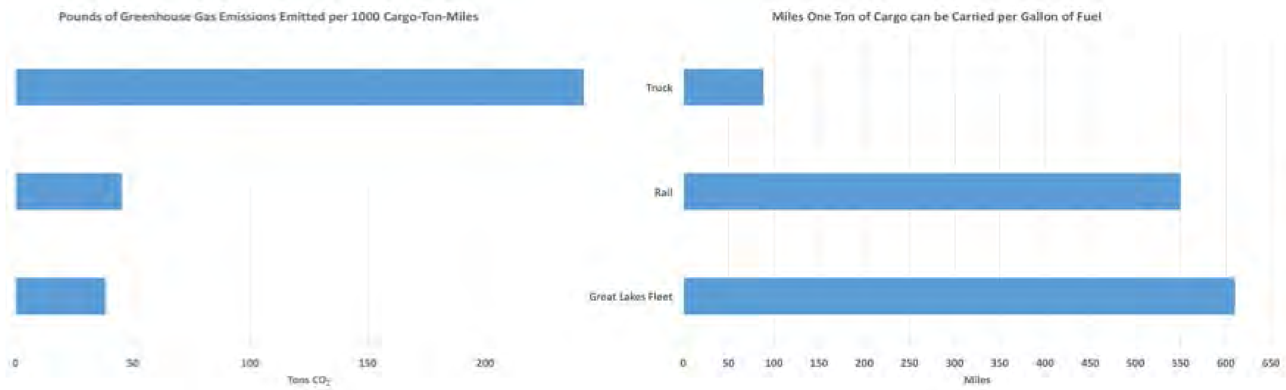

FIGURE 30—CARBON DIOXIDE (CO^2) EMISSIONS AND GALLONS OF FUEL USED TO MOVE CARGO

The Lakers are a highly efficient and safe mode of transportation in comparison to rail transportation. The DOT reports that fatality rates are 23 times higher and injury rates 125 times higher in the rail industry than the Laker industry.[160] Similarly, the USACE and DOT estimated that the Lakers are more fuel-efficient and produce less carbon dioxide than any other mode of transportation (see Figure 30).[161] Rail produces about 20 percent more carbon dioxide, and are about 13 percent less fuel efficient, than Lakers.

MOVING IRON ORE BY TRUCK

There are not enough trucks, or drivers, in the Nation to move the iron ore from the mines to the mills.[162] Each One Thousand Footer Lake Carrier carries approximately 70,000 tons of iron ore, which is equivalent to about 3,000 trucks. The mills use the 70,000 tons about every five days, which means that 600 trucks per day--1 truck every 2.4 minutes--would have to enter a steel mill, drop its load and leave. To bring trucks to 7 mills would mean that, for every point on the Interstate Highway System between Minnesota and Indiana, there would be a truck loaded with iron ore passing every 20 seconds on one side of the road and one truck returning empty on the other side of the road. The Interstate Highway System would have to be shut down to all traffic except for the iron ore trucks and no road maintenance could occur.

As stated earlier, most steel mills are designed to receive iron ore by Lake Carriers and cannot accept iron ore by truck. At some mills, there is no means to get a truck to the area where the iron ore is stored. Trucks are used extensively to move finished products from the mills; one steel mill reported that 400 - 500 trucks a day transport products to customers.

Lakers are a more efficient and safer mode of transportation than trucks. DOT reports that fatality rates are 155 times higher and injury rates are 2172 times higher transporting cargo by truck than by Laker.[163] The Lakers are more fuel-efficient and produce less carbon dioxide (CO_2) than trucks.[164] Trucks produce about 11 times as much CO_2 and uses about 10 times as much fuel to move cargo compared to Lakers.

Finally, OCIA-NISAC estimates that the cost of moving iron ore by truck is approximately four times the value of the iron ore itself and would likely be cost-prohibitive in addition to impractical.

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160 U.S. Department of Transpiration/Maritime Administration, "Waterways: Working for America," at http://www.marad.dot.gov/documents/water_works_REV.pdf, accessed February 5, 2015.
161 USACE, "Great Lakes Navigation System: Economic Strength to the Nation," at http://www.lre.usace.army.mil/Portals/69/docs/Navigation/GLN_Strength%20to%20the%20Nation%20Booklet2013v2_final2w.pdf, accessed February 6, 2015.
162 Under current economic conditions, trucking companies face a dearth of truck drivers (see, Journal of Commerce, "The Driver Shortage," on June 24, 2015 at http://www.joc.com/special-topics/driver-shortage, accessed June 24, 2015).
163 U.S. Department of Transportation/Maritime Administration, "Waterways: Working for America," at http://www.marad.dot.gov/documents/water_works_REV.pdf, accessed February 5, 2015.
164 USACE, "Great Lakes Navigation System: Economic Strength to the Nation," at http://www.lre.usace.army.mil/Portals/69/docs/Navigation/GLN_Strength%20to%20the%20Nation%20Booklet2013v2_final2w.pdf, accessed February 6, 2015.

SHIPPING IRON ORE THROUGH THE PORT OF ESCANABA

FIGURE 31—CN ORE DOCK AT ESCANABA, MICHIGAN

Currently, the Port of Escanaba could provide only limited mitigation during a closure scenario. The CN Railway Ore Dock in Escanaba, Michigan is the only port downbound of the Soo Locks that is able to load iron ore (see Figure 31). However, the Port of Escanaba is the smallest iron ore port in Minnesota or Michigan; it is about 20 percent smaller than the next smallest port (Silver Bay, Minnesota) and 20 percent the size of the largest port (Two Harbors, Minnesota). Escanaba currently ships about 7 percent of the iron ore mined, a number that has been stable since at least World War II.[165] Escanaba is too far from the mining centers to compete in cost with the Lake Superior iron ore docks. As an example, the rail distance from Minntac to Duluth is about 70 miles; from Minntac to Escanaba is about 350 miles. The extra rail distance means additional shipping costs at rail rates, which are higher, on a ton per mile basis, than the waterborne rates.

The infrastructure at Escanaba has not been maintained and the capacity of Escanaba continues to decline. Most of the iron ore that transits Escanaba originates out of the Empire Mine in Michigan. The Empire Mine has been expected to close for a number of years, most recently in 2014. However, ArcelorMittal and Cliffs Natural Resources agreed to extend the life of the Empire Mine until at least January 2017.[166] Without a long-term customer, CN Railway is not expected to invest significant resources at the Port of Escanaba.

Even if it surges to maximum capacity, in its current state, Escanaba could handle only about 10 percent of the total annual iron ore requirements of the Great Lakes steel mills. Essentially all of the iron ore that transits the

165 Morgan, John P. "The Domestic Mining Industry of the United States in World War II," Government Printing Office: Washington, 1949.
166 UpperMichigansSource.com, "Empire Mine Avoids Closure through New Ore Deal," on February 27, 2014 at http://www.uppermichiganssource.com/news/story.aspx?id=1012772#.VXY0R2BiXJQ, accessed June 2, 2015.

Port of Escanaba goes to Indiana Harbor (ArcelorMittal) and Middletown (AK Steel). An insufficient amount of iron ore could move through Escanaba to operate Indiana Harbor efficiently. While it is possible that enough iron ore could be moved to operate one of the three blast furnaces at Indiana Harbor, the overall capacity utilization of Indiana Harbor would be about 33 percent. Iron ore would likely continue to move through Escanaba to Middletown (see Table 4).

LIGHTERING

FIGURE 32—LIGHTERING EXAMPLE

Lightering is the process of transferring cargo (in this case, iron ore) from a Poe-sized Laker to a MacArthur-sized Laker for transit through the MacArthur Lock and then from a MacArthur-sized Laker to a Poe-sized Laker for transit to the steel mills (see Figure 32). Lightering occurs periodically on the Great Lakes. The most common occurrence is when a Laker is disabled and the iron ore must be off-loaded onto another Laker. Lightering may also occur if iron ore is being sold onto the seaborne market and the commodity must be moved onto a smaller Laker that can transit the Welland Canal through the Saint Lawrence Seaway.

However, a significant number of logistical issues would challenge the ability to undertake lightering successfully:

- The Poe and MacArthur Locks are among the busiest in the world, so to move all traffic through a single lock would cause significant congestion;

- Beginning in September the weather turns unfavorable, making lightering past August questionable.
- Lightering can only occur if wave heights are forecast to be less than 1 meter during the off-loading and on-loading period.[167] To off-load and on-load a Poe-restricted Laker onto 2-3 MacArthur-sized Lakers and from the MacArthur-sized Lakers to a Poe-restricted Laker could take more than 24 hours;[168]
- Loading from a MacArthur-sized Laker to a Poe-restricted Laker requires specialized equipment that does not exist in sufficient capacity. The Poe-restricted Lakers are significantly higher off the water and the self-unloading structures on the MacArthur-sized Lakers cannot properly align; and
- Under current use, the 70-year-old MacArthur Lock closes for a number of hours each month for repair. Constant usage is likely to increase the need for repair and unanticipated closures. Currently, the MacArthur Lock does not open for at least 2 weeks after the Poe Lock opens. Reliance on the MacArthur Lock would entail a delay.

Lightering could also be encumbered by a number of contractual obstacles regarding:

- Which iron mines have priority to ship;
- Which steel mills would have priority for receipt;
- How the grain and coal that would normally move on the displaced Class VIII Lakers would get to their destination and identifying the responsible party to pay for the transportation price differential.

To address the concern about whether coal shipments are necessary, OCIA-NISAC analyzed a potential disruption of coal deliveries to the major coal-fired generation facilities on the southeastern portion of Michigan. Although transporting coal by freighter is more cost-effective, there does not appear to be a logistical requirement to use freighters over rail transportation. Currently, coal is currently railed from Wyoming to Wisconsin and then placed on a Laker. If the coal had to be moved the full distance on rail lines, about 400 additional rail cars (4 unit trains) a day would be needed to move the longer distance.

Even if additional rail cars cannot be located or congestion in the Chicago area inhibits the ability to move 4 unit trains a day, coal may not be critical to maintain Michigan automobile production, provided that iron ore was being delivered. The Los Alamos National Laboratory contingency analysis on behalf of OCIA-NISAC suggests that other generators in Michigan and neighboring regions can make up the lost generation. The analysis indicated that this shift in generation would cause no major overloads or voltage problems within the regional transmission system. The regional operators could also reduce demand by implementing interruptible contracts during peak load periods. The loss of coal movements through the Soo Locks does not appear to affect the ability of Michigan automobile manufacturers to continue their operations. For a more complete discussion, please see Appendix G.

IMPORTING FOREIGN ORE

Using imported iron ore from Canada or another country is not considered possible. Industry experts indicate that iron ore pellets are not interchangeable; steel mills are designed to receive specific types of pellets from specific mines in order to meet customer specifications. Different iron ore grades from different mines affect the grade of steel produced at a mill.[169] Therefore, imported iron ore would require additional testing, materials, and time to ascertain how to convert the seaborne iron ore into specified steel products.

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167 This corresponds generally to a wind speed of less than 12 miles per hour (University of North Carolina, "Beaufort Scales (Wind Speed), on May 31, 2001 at https://www.unc.edu/~rowlett/units/scales/beaufort.html, accessed February 26, 2015, though wave height also depend on bathymetry (underwater topography) and fetch (the distance over water that wind blows in a single direction).

168 The lightering estimates were based on analysis done by USACE for an Expert Elicitation Workshop on lightering.

169 Footnote 1 describes the process of creating the taconite pellets. As part of the process, various chemicals can be added to the extracted iron ore to make taconite pellets. Depending on the type of steel to be made, different chemicals are added. Therefore, the processed taconite pellets have been developed for a specific mill to make a specific type of steel. These taconite pellets are not interchangeable. Further, seaborne iron ore from Australia and Brazil is actually iron ore and taconite. The U.S. blast furnaces are not configured to accept iron ore without changing processes, which could result in a significant amount of testing, up to a year as previously stated, to determine that the steel is manufactured to the exact same specifications.

In any case, only a limited amount of iron ore, possibly 1 to 2 million tons, could be moved through Canada's St. Lawrence Valley, far less than the 45 million tons shipped out from Minnesota and Michigan.[170] Additionally, the price of seaborne iron ore (typically from Brazil or Australia) can diverge significantly, higher or lower, from Minnesota iron ore prices. This does not include the substantial transportation cost differentials and other logistical challenges. For instance, the transit time from the iron ore Port of Tubarao in Brazil to Gary, Indiana is four times the transit time from Duluth, Minnesota to Gary, Indiana. Further, the size of the Welland Canal restricts traffic on that portion of the St. Lawrence Seaway to Lakers having far smaller capacity than the Lakers that carry iron ore. The locks in the Saint Lawrence Seaway can handle Lakers that are only slightly larger than MacArthur-sized Lakers, meaning that each Laker would hold about 30 percent less iron ore than the typical Laker. However, one of the biggest hindrances may be the unique nature of the Great Lakes shipping fleet. According to a review of the Lloyds Registry of shipping vessels, there are almost no self-unloading vessels outside of the Great Lakes.[171,172] The ports and mills along the Great Lakes have limited capabilities to unload the type of traditional bulk carrier used elsewhere in the world.

Almost all steel mills today are part of vertically integrated corporations that include ownership interests in iron ore mines, dating back to 1900 in some cases.[173] ArcelorMittal and U.S. Steel directly own iron ore mines and steel mills, while A.K. Steel owns an equity interest in an iron ore company in addition to their steel mills. Essar Steel, which owns the Algoma Steel Mill in Sault Ste. Marie, Ontario and Cliffs Natural Resources, which owns iron ore mines but not steel mills, are the only companies that are not vertically integrated. Many of the steel mills that went bankrupt in the 1970-2000s were firms that imported iron ore and could not withstand the volatile cost differentials between Great Lakes iron ore and seaborne iron ore.[174]

IMPORTING STEEL

The first action many firms will take is to obtain, or attempt to obtain, appropriate steel slabs from overseas. This is more likely to be possible for automobile parts less reliant on specialized steel. This would be a short-term solution designed to keep automobile lines going for as long as possible. At best, industry executives believe that this would keep some lines going for a couple of weeks and is a means of extending the use of the existing steel supply. It is conceivable that cargo planes would be used to carry steel slabs or steel coils, a very expensive proposition. Industry executives stated that cargo planes have been used in the past during other disruption events. Subaru, which accounts for about 3 percent of the North American automobiles sales, reported that it spent $60 million a month flying in auto parts due to the labor difficulties at the Ports of Los Angeles/Long Beach in the first quarter of 2015.[175] Other, larger Asian automobile firms, reportedly spent far more to keep their production lines operational.

For a disruption of 6 months or longer, industry executives are divided on whether steel slabs can be imported. Automotive quality steel is available in Japan, in Europe, from POSCO in South Korea, and from Boasteel in China. However, there are a number of limits on the ability to import steel from these locations:

- Changing the types of steel used in automotive production requires significant trials, validation, and inspections;

170 Baird/URS, "Soo Locks Partial Benefits Analysis: Foreign Sourcing Alternative," undated.
171 From a meeting with the USACE, February 19. 2015. The foreign self-unloading vessels are too large to transit the Welland Canal and therefore cannot enter the Great Lakes.
172 Self-unloading vessels first appeared on the Great Lakes in 1908 though they did not become widespread until the 1970s (see DOT/Maritime Administration, "Status of the U.S. Flag Great Lakes: Water Transportation Industry," on February 2013 at www.marad.dot.gov/documents/US-Flag_Great_Lakes_Water_Transportation_Industry_Final_Report_2013.pdf, accessed March 10, 2015). They are not in use outside of the Great Lakes because of the differences in use. Vessels in the Great Lakes fleet pick up their cargo and drop it off 2 days later, returning to pick up more cargo. Thus, shortening the time in port is critical. Conversely, seaborne freighters travel for weeks from origination to destination and a few additional hours in port is not worth the loss of capacity or increased weight associated with the self-unloading equipment.
173 Rogers, Robert, "An Economic History of the American Steel Industry," Routledge: New York, 2009.
174 AK Steel holds equity interests in the Bovey Mine and the Keewatin Mine. ArcelorMittal owns the Minorca Mine and holds equity interests in the Hibbing Mine and the Empire Mine. U.S. Steel owns the Keetac Mine and the Minntac Mine and holds equity interests in the Tilden Mine and the Hibbing Mine. Cliffs Natural Resources is the only independent iron ore firm, which owns the Northshore Mine and United Taconite. Cliffs also holds equity interests in the Hibbing Mine and the Empire Mine.
175 Reuters, "Japan Automakers Hit Production Snags as U.S. Port Dispute Drags On," on February 6, 2015 at http://www.reuters.com/article/2015/02/06/us-usa-ports-japan-idUSKBN0LA0MR20150206?feedType=RSS&feedName=businessNews, accessed June 22, 2015.

- The lack of infrastructure in domestic ports, and the lack of availability of ships, trucks and drivers, railcars, locomotives, and crew, are limiting factors. To illustrate this point, approximately 41.8 million tons of steel can be made by the steel mills listed as Non-Operating Steel Mills because of the disruption (see Table 4). Each steel coil weighs about 30 to 40 tons; for purposes of simplicity, will be assumed to weigh 33.33 tons. Therefore, to make up for the 41.8 million tons in lost capacity under this scenario, 1.25 million slabs would have to be transported from a port to a steel-rolling facility. One truck could carry one slab, which means it would take 1.25 million truck trips, or over 24,000 truck trips a week. One train could take three slabs per railcar. For a unit trail of 100 cars, this would be 300 slabs per train on 80 unit trains a week. Industry experts stated that the amount of infrastructure necessary to move this amount of slabs does not exist;
- Even if a manufacturer could import steel coils, there are additional logistics challenges. Steel coils are delivered to customers either by railcar or truck depending on the preferences of the purchaser. The preferences can be so specific as to designate how the steel coils are placed on a truck so as to line up properly with the receiving dock. If steel coils were imported through a port, which would have to be either along the Eastern Seaboard or at some unidentified point on the Gulf Coast, the steel coils would have to move from rail or barge to truck. Moving these 30 to 40 ton steel coils without damaging them in the transfer may be problematic;
- Foreign steel companies are not in the business of selling steel slabs, which is a lower profit venture. If the slabs could be rolled overseas, the coils would likely degrade during shipment to North America;[176]
- In 'normal' economic times, it is highly unlikely that sufficient excess supply of steel would be available, particularly of the steel quality needed for automotive production. For instance, a number of industry executives stated that they would look to Boasteel of China and POSCO of South Korea as potential alternative sources of steel. Boasteel produces about 44 million tons of steel[177] and Posco about 38 million tons.[178] The North American demand for automotive steel is likely around one-half of the combined output of these two companies, if one assumed that their entire output was automotive quality steel, which it is not. While there is insufficient information to do a complete analysis, the spare automotive steel capacity of these two firms is probably fairly small;
- To obtain sufficient quantities of steel, if even available, would take at least 3-4 months, and likely significantly longer;
- Some industry executives reported that there may be legal or contractual restrictions that would inhibit the ability to import foreign steel slabs; and
- The cost of importing steel slabs would be significantly higher than the current price of steel. While the price differential has not been estimated, the cost of cars would either have to rise significantly to cover the price differential, or firms involved in the supply chain would have to cover the costs out of their available capital, which is not sustainable.

It has been suggested that foreign automobile companies are more likely to have overseas sources that could produce steel slabs manufactured to the correct specifications and moved to the United States. Industry executives have stated that these firms generally manufacture automobiles to similar specifications in their home markets in Asia or Europe and in the North American markets. However, most foreign automobile manufacturers have moved their supply chains to the local markets, leaving little excess production capacity in their home market. As an example, the Japanese automotive companies make almost all of their cars for the North American market in North America. As the Japanese economy has restructured over the past 30 years, few cars are made in Japan for export into the North American market.

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176 According to at least one industry executive, slabs cannot be rolled overseas for transportation to the United States due to environmental issues that would cause the coils to degrade.
177 Boasteel, "Brief Introduction," at http://www.baosteel.com/group_en/contents/2880/39991.html, accessed June 15, 2015.
178 POSCO, "2015 Investor Forum," on February 5, 2015 at http://www.posco.com/homepage/docs/eng3/dn/invest/archive/2015_investors_forum_eng.pdf, accessed June 15, 2015.

INCREASE IRON ORE INVENTORY AT STEEL MILLS

Maintaining a 6-month inventory of iron ore at the steel mills could mitigate the impacts of a closure. However, some steel mills do not have the storage capacity to maintain this type of inventory and no company likely has the available capital to tie up in precautionary inventory for an event that has never occurred.

INCREASE STEEL INVENTORY IN THE AUTOMOTIVE SUPPLY CHAIN

Maintaining a precautionary supply of steel in the automotive supply chain is not considered feasible. Almost every part of an automobile has a unique steel coil that consists of a different recipe, dimension, and elasticity. Environmental issues and age degrade the quality of the steel coil, some of which degrade to the point that, within 90 days, they may not be usable.[179] Different types of steel coil cannot be substituted without extensive analysis and new crash tests, which have very long process times. Something seemingly as simple as painting the steel body requires testing because different types of paints adhere to the different types of steel differently. In fact, automotive manufacturers do not select paints because the paints adhere to the steel; rather, they select steel because the steel adheres to the paint.

CHANGING AUTOMOBILE PRODUCTION FROM STEEL TO ALUMINUM

It would be not be feasible for the automotive manufacturers to switch from steel to aluminum under the closure scenario. As an illustration, Ford Motor Company started production of a new F-150 truck with an aluminum body replacing the traditional steel body.[180] While the body is made with aluminum, the frame and other parts are still made with steel. In addition, the retooling of the Dearborn truck factory cost over $840 million and shut down production for over 2 months, even with extensive advance planning. Because of higher production costs, the sticker price of the aluminum F-150 is about $3000 per vehicle higher than the truck with the traditional steel body.[181] The production of an aluminum body is more complicated than that of the traditional steel production; “many steps are jammed into the same amount of time it takes to make a steel body assembly.”[182] As one industry executive put it, aluminum stamping and welding is more akin to aviation production than automobile production.

In any case, there is an insufficient amount of aluminum production capacity to meet additional automotive needs.[183] Domestically, five companies operate 10 aluminum smelters with annual production capacity of approximately 2.7 million tons, compared to the estimated 30.0 million tons of steel used annually in automotive production. Worldwide capacity of aluminum is approximately 61.9 million tons with about 16.0 million tons of idle capacity.

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179 Steel is coiled to make it easier to transport, with each coil averaging about 30 - 40 tons (see Figure 4). Stamping plants will take the coil, unroll them, and then cut and form the particular automotive parts.

180 Automotive News, “Inside Ford’s Retooled F-150 Plant,” November 16, 2014, at www.autonews.com/article/20141116/OEM01/311179981/inside-fords-retooled-f-150-plant, accessed January 9, 2015.

181 Tech Times, “Ford Retooling Plant for Aluminum F-150, Assembly Line Shuttering for Two Months,” August 26, 2014, at www.techtimes.com/articles/14089/20140826/ford-retools-production-plant-build-new-f150.htm, accessed January 9, 2015.

182 Automotive News, “How will Ford Build the Aluminum F-150?” April 28, 2014 at www.autonews.com/article/20140428/OEM01/304289997/how-will-ford-build-the-aluminum-f-150, accessed January 9, 2015.

183 An independent economist reported that all available aluminum capacity was purchased to make the Ford F-150.

POTENTIAL MITIGATION STRATEGIES

A combination of strategies will likely be required to mitigate the disruptions caused by an unexpected closure of the Poe Lock. While OCIA does not have a specific set of recommendations, the following are suggestions for further analysis.

TWINNING AND UPGRADING THE POE LOCK

The creation of a second Poe-sized lock—"twinning the Poe Lock"—would mitigate most failure scenarios.[184] USACE has developed a plan, awaiting Congressional funding, to construct a second Poe-sized lock by combining the shuttered Sabin and Davis Locks. According to USACE, the current working estimate for construction of the entire project is $580 million, last updated in 2009, and will take 10 years to complete.[185,186] This project would mitigate the impact of situations in which only the Poe Lock is disrupted. The second Poe-sized lock must be built to the same specifications as the existing Poe Lock; building a lock with larger dimensions would lead shippers to build larger Lakers, causing the same single point of failure situation that exists currently. This is a cycle that has repeatedly occurred in the past; each time a new, larger lock was built, the dimensions of new ships were stretched to make the most of the new dimensions.[187]

USACE estimates of the remaining cost of upgrading at around $87 million, according to its asset renewal plan for the Soo Locks.[188] This plan shows that some of the infrastructure to be updated either has failed or is in the process of failing. Examples include the electrical system for the MacArthur Lock, which was built in 1943; leaking valve bulkheads on the MacArthur Lock; the Poe Lock hydraulic system; gate anchorages, a new set of gates for the Poe Lock, and miter and quoin block rehabilitation for the Poe Lock. Other significant infrastructure is listed as inadequate or poor. A full upgrade of the Poe Lock could require its complete shutdown for 6 to12 months, which could only be done if there were a twin lock.

A STRATEGY TO IMPROVE RESILIENCE

To ensure resilience, feasible strategies must be developed that do not rely on passage through the Soo Locks, even with a second Poe-sized lock. With only 400 feet between the Poe Lock and the to-be-constructed lock, many failures or event scenarios could affect both locks, disrupting the supply chain.

There is no single strategy to bypass the Soo Locks. OCIA-NISAC analysts suggest a series of considerations for further study. A set of strategies agreed-to ahead of a disruption event, with proper authorities and buy-in from all parties, is necessary to maintain a sufficient supply of iron ore to the integrated steel mills.

SUGGESTIONS TO MITIGATE AN IRON ORE SHORTFALL

About 49.6 million tons of iron ore move through the Great Lakes over the course of the navigation year, from March 25 through January 15 for the Soo Locks, and year-round for the Port of Escanaba. This represents the average amount of iron ore shipped over the past four years. Based on conversations with industry executives and OCIA-NISAC analysis, the following is a suggested path to meeting this goal of 49.6 million tons shipped:

- Once the Poe Lock re-opens on September 25, approximately 16.1 million tons could be shipped during the remainder of the navigation season.

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184 Lake Carriers Association, Second Poe-Sized Lock," on April 17, 2013 at http://www.lcaships.com/2013/04/17/second-poe-sized-lock/, accessed March 28, 2015.
185 USACE, "Great Lakes Navigation System: Economic Strength to the Nation," at http://www.lre.usace.army.mil/Portals/69/docs/Navigation/GLN_Strength%20to%20the%20Nation%20Booklet2013v2_final2w.pdf, accessed January 1, 2015.
186 One of the concerns about the 10-year time horizon for constructing a new lock regards a prior discussion of steel. There, the analysis points out that BOF steel and EAF steel are not interchangeable because BOF steel has the property of formability. The metallurgy can be controlled to a far greater degree when one starts with iron ore and not scrap steel. However, EAF steel continues to improve and could get to a point where mini-mills could provide the necessary steel to automotive companies, particularly in a crisis.
187 Thompson, Mark L. "Steamboats & Sailors of the Great Lakes," Wayne State University Press: Detroit, 1991.
188 USACE, "Soo Locks Asset Renewal Plan," on February 2012.

- While the Port of Escanaba is the smallest of the iron ore docks, there is room to expand operations there significantly. A number of industry executives stated that the Port of Escanaba could be renovated and enlarged to handle 15.0 million tons of iron ore. These 15 million tons would far exceed both the current shipments through Escanaba and the anticipated surge level of about 5.5 million tons. In addition to the port renovation, significant upgrades to the rail system in the area would be necessary.[189] There is historical precedent to consider the Port of Escanaba as part of a mitigation strategy. The Soo Locks was recognized as a single point of failure during WWII. In December 1940, President Roosevelt ordered an engineering study to consider an 'overland ship railway' that would allow fully loaded iron ore carriers to be hoisted out of the water, placed on trains, and sent, by rail, around Saint Marys River.[190,191] While that plan was not technically feasible, a new plan emerged in August 1942. Under this plan, Escanaba, being the only port downstream of the Soo Locks, would be expanded to 60 million tons.[192] This was seen then as merely an emergency backup for the Soo Locks. After the initial phases of construction, lumber shortages and a re-assessment of the German threat led to the termination of the project. The docks that had been constructed were razed and the material used for other purposes.
- There are six steel mills that are in Table 4 as a Non-Operating Steel Mill that either have some rail access or could, with relatively minor modifications, receive some iron ore by rail. Excluding Middletown (AK Steel) that is anticipated to operate at 82 percent, the other five are: Ashland (AK Steel), Cleveland (ArcelorMittal), Gary Works (U.S. Steel), Great Lakes Works (U.S. Steel), and Mon Valley Works (US Steel). Ashland (AK Steel) and Mon Valley Works (U.S. Steel) currently receive steel by rail, after it has been trans-shipped at a Lake Erie dock.[193] Gary Works (US Steel) and Great Lakes Works (U.S. Steel) have very limited capability to receive iron ore by rail, and probably have not done so in years to decades.[194] Given the rail constraints discussed previously, rail, en masse, is not a likely course of action. However, a smaller use of rail may be feasible. If two unit trains a week made deliveries to two of the six previously mentioned steel mills, over the course of the year, approximately 1.0 million tons of iron ore could be delivered. In order to undertake this, four unit trains would probably be necessary as well as some degree of upgrading to the rail infrastructure at the steel mills. Plans to mitigate rail congestion between Minnesota and Indiana, and in particular, the Chicago area, would be necessary.
- Many of the integrated steel mills along the Great Lakes have space to store significant amounts of iron ore. However, companies are unlikely to tie up significant working capital in preventive inventory for an event that has not occurred. Still, the U.S. Government should explore avenues that may make the storing of a preventive inventory palatable. A strategic iron ore stockpile that could provide a six-month supply of iron ore may be warranted. Even if a closure were to extend beyond 6 months, the 6-month supply would provide time to develop alternatives.[195] To meet the 49.6 million ton requirement, 16.5 million tons of storage would be necessary after taking into consideration other mitigation strategies.[196] Initial OCIA-NISAC analysis, and discussions with industry executives, suggest that this is logistically feasible. The iron ore pellets generally are not subject to environmental degradation. One industry executive reported that when iron ore supplies ran short in April 2014, they used a pile of iron ore pellets that had been sitting in a rejected pile since 2000. Another executive stated that iron ore pellets have been dredged from lake bottoms after being submerged for 20 years and used.
- The three Northern Indiana plants—Burns Harbor (ArcelorMittal), Gary Works (U.S. Steel), and Indiana Harbor (ArcelorMittal)—each have a functioning sinter plant. This means that they could receive

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189 There may be locations along the Lake Superior side of the Soo Locks where iron ore could be dumped and then railed to Escanaba. This alternative would permit Lakers to carry iron ore to the dumping site and then it may be a shorter route to Escanaba There is no specific site considered. Any options may require the purchasing or condemnation of existing property and the completion of environmental impact statements.

190 Escanaba Daily Press, "History of Escanaba and Lake Superior Railroad," on December 27, 1950 at http://www.michiganrailroads.com/RRHX/Stories/E&LSHistory.htm, accessed April 26, 2015.

191 Joachim, George J., "Iron Fleet: The Great Lakes in World War II," Wayne State University Press: Detroit, 1994.

192 Ibid.

193 Cleveland (ArcelorMittal) receives its iron ore at the Cleveland Bulk Terminal (CBT). While CBT does not have current capacity to receive iron ore by rail, industry executives believe that, logistically, it could be done.

194 OCIA-NISAC has no information on the rail accessibility of Dearborn (AK Steel).

195 Storage facilities would need to maintain various mixes of different types of iron ore. Depending on economic conditions, the iron ore may be secured from either domestic or foreign sources.

196 OCIA-NISAC would suggest some additional amount of iron ore by stockpiled in order to control for some possible degrading of iron ore, and to keep a broader mix of pellet types.

seaborne iron ore. Industry executives suggest that 5 percent of the iron ore needs could be met with sinter. This could provide about a 1-million-ton cushion.

OTHER CONSIDERATIONS

OCIA-NISAC is uncertain as to whether all relevant stakeholders have been engaged regarding the legal and logistical challenges facing a successful lightering process. Lightering would reduce disruptions to the automotive, appliance, farm equipment, and construction and mining machinery industries, but the contractual challenges must be considered.

A designated place or places must be predetermined to receive limestone, which would only be required if MacArthur Lock was also closed. Some possibilities include Green Bay, Wisconsin, Manitowoc, Wisconsin, or Cleveland, Wisconsin. The limestone would then be railed to the pelletizing plant. A significant percentage of the iron ore pellets production depends on the availability of limestone.

CONCLUSIONS

In terms of an impact to the North American economy, it is hard to conceive of a single asset more consequential than the Poe Lock. As outlined in the report, 10.9 million jobs in the United States, and possibly upwards of 13 million jobs in North America, are likely dependent on the functioning of the Poe Lock. An unprecedented supply shock could affect North America if the closure scenario were to occur. The United States has historical knowledge of how to respond to shocks caused by financial crises, oil prices or availability, or falling aggregate demand. There is no similar guide for responding to a supply shock that incapacitates a large set of industries.

As documented in this report, the iron mining - integrated steel production - manufacturing, particularly automobile manufacturing, supply chain, is not only consequential, but potentially one of the least resilient supply chain in North America. The relationship between the steel mills and the auto assembly plants is complex. There is a different steel coil for just about every part of an automobile made with steel, and collectively, there are reportedly some 1500 different recipes of steel for the automotive industry. Without the steady stream of iron ore coming from Lake Superior through the Poe Lock, many or all of these 1500 different steel recipes cannot be made. The inability to make just one recipe could stop production of a particular automobile; the inability to make a couple of recipes could stop production for a particular automotive company; and the inability to make a few recipes could stop production of all North American automotive production. Historically, the lack of a single part has caused automobile production to shut down.

The current lack of resilience does not mean that measures cannot be taken to mitigate a potential closure scenario. Engagement and planning among the relevant stakeholders may allow for the iron mining - integrated steel production - manufacturing supply chain to remain viable even in the face of a prolonged closure of the Poe Lock. The actions taken and considered during World War II suggest a course of action. This report documented three steps that were taken: a new lock, the MacArthur Lock, was constructed; the building out of the rail infrastructure to the Port of Escanaba coupled with the expanding of the port was considered; and a large contingent of troops were garrisoned. While the latter action was in response to the perceived overt threat, the two prior actions could do much to improve resilience. In addition to the other actions suggested in the Potential Mitigation Strategies section, resilience could be built into the system.

However, the critical aspect must be the focus on a plan to deal with a potential Poe Lock failure. As one industry expert put it, "the game plan needs to be in the book, because everyone will be scrambling."

APPENDIX A: IRON ORE MINES

TABLE 7—IRON ORE MINES

Name	Location	Owner	Capacity (M tons)[197,198]
Bovey	Bovey, MN	Magnetation 100 percent[199]	1.2
Keewatin	Keewatin, MN	Magnetation 100 percent	0.4
Keetac	Keewatin, MN	U.S. Steel 100 percent	6.0
Hibbing Taconite	Hibbing, MN	ArcelorMittal 62 percent Cliffs Natural Resources 23 percent U.S. Steel 15 percent	9.0
Minntac	Mt. Iron, MN	U.S. Steel 100 percent	16.0
United Taconite	Eveleth, MN	Cliffs Natural Resources 100 percent	5.9
Minorca Mine	Virginia, MN	ArcelorMittal 100 percent	3.1
Northshore Mining	Babbitt, MN	Cliffs Natural Resources 100 percent	6.9
Empire Mine	Negaunee, MI	Cliffs Natural Resources 79 percent ArcelorMittal 21 percent	6.2
Tilden Mine	Tilden, MI	Cliffs Natural Resources 85 percent U.S. Steel 15 percent	9.0
Minnesota Taconite Operation[200]	Hibbing, MN	Essar Steel 100 percent	Under development (7.7 when complete)

197 Iron mines report capacity and production in long tons or metric tons while freighters and steel mills report in short tons. Therefore, to make comparisons more direct, iron ore capacities were converted into short tons.
198 A number of mines do not operate at their rated capacity as discussed in the section entitled, "Iron Ore Mining Assumptions."
199 Magnetation LLC owns 100% of the Bovey and Keewatin operations. A.K. Steel is a 49.9 percent owner of Magnetation LLC.
200 Essar Steel's mine is expected to be operational in 2016 and will likely supply both the Algoma Steel Mill (Essar Steel) and replace the Empire Mine's shipment of iron ore to Indiana Harbor (ArcelorMittal). As the Empire Mine will close in 2016-2017, Indiana Harbor's purchase of iron ore from Essar Steel will increase the dependency on the Soo Locks as the Empire Mine shipped out of Escanaba. (see Essar, "Essar Steel Minnesota LLC Signs a Landmark Iron Ore Pellet off Take Agreement with ArcelorMittal USA) on February 11, 2013 at http://www.essar.com/article.aspx?cont_id=LOiyw6+HI40=, accessed April 11, 2015. However, industry executives have said that Essar has not secured any means to ship the iron ore out of Minnesota. All available space at the Lake Superior iron ore docks are fully committed. This project has faced numerous delays and there is some skepticism whether the mine will open.

APPENDIX B: NORTH AMERICAN INTEGRATED STEEL MILLS

TABLE 8—STEEL MILLS

Name	Location	Owner	Steel Products	Capacity (M tons)
Algoma	Sault Ste. Marie, ON	Essar Steel	Automotive, construction, energy, manufacturing, mining, shipbuilding,	2.8
Ashland	Ashland, KY	A.K. Steel	Automotive, electrical steel, stainless steel, service centers	2.6
Burns Harbor	Burns Harbor, IN	ArcelorMittal	Appliances, automotive, construction, office furniture and rail cars	5.0
Cleveland	Cleveland, OH	ArcelorMittal	Automotive, service centers, converters, plate slabs and tubular applications	3.8
Dearborn	Dearborn, MI	A.K. Steel	Automotive	2.5
Dofasco	Hamilton, ON	ArcelorMittal	Automotive, appliances, construction, container, tubular	4.5
Fairfield Works	Birmingham, AL	U.S. Steel	Construction, tubular, metal building, automotive, appliance	2.4
Gary Works	Gary, IN	U.S. Steel	Automobile, appliance, container, metal building, home construction	7.5
Granite City Works	Granite City, IL	U.S. Steel	Tubular, construction, container, automotive	2.8
Great Lakes Works	Ecorse, MI	U.S. Steel	Automotive, container	3.8
Indiana Harbor	East Chicago, IN	ArcelorMittal	Automotive, appliance, office furniture, agricultural, construction, pipe and tube, electrical/motor lamination, converters and steel service centers	9.5
Lake Erie Works	Nanticoke, ON	U.S. Steel	automotive, construction, infrastructure, appliance, manufacturing and pipe and tube industries	3.7
Middletown	Middletown, OH	A.K. Steel	Automotive, electrical steel, stainless steel, service centers	2.9
Mon Valley Works	Braddock, PA	U.S. Steel	Appliance, construction	2.9

APPENDIX C: THE GREAT LAKES FLEET

The U.S. Great Lakes bulk carrier shipping fleet consists of 48 Lakers. Slightly over one-half of the fleet is Poe-restricted, meaning that it can only transit the Soo Locks through the Poe Lock. Twenty Lakers can use either the Poe or the MacArthur Lock. However, the Poe-restricted Lakers are significantly larger, with an average capacity of over 51,000 net tons compared to less than 25,000 net tons for the smaller Lakers. Approximately three-quarters of the carrying capacity is on Poe-restricted Lakers.

The Poe-restricted and the MacArthur-sized Lakers have significantly different functions. Poe-restricted Lakers, particularly the 13 one-thousand footers that make up 46 percent of the total Great Lakes Laker carrying capacity and 62 percent of the Poe-restricted carrying capacity, are almost exclusively used for long haul trips from Lake Superior to the three Northern Indiana integrated steel mills, Detroit, and most of the Ohio iron ore docks. The commodities are almost exclusively one-way deliveries of iron ore or coal with no pick up of commodities to transit upstream through the Poe Lock. The MacArthur-sized Lakers generally work shorter trips carrying a variety of commodities to various ports. These trips may include carrying grain downstream for foreign export or iron ore to steel mills that cannot accept the larger Lakers (i.e., AK Steel Dearborn, ArcelorMittal Cleveland). However, unlike the Poe-restricted Lakers, the MacArthur-sized Lakers may carry products, particularly limestone, upstream through the Soo Locks.

Industry executives assert that many, if not most, Lakers are under long-term charter at the beginning of the shipping season.

USACE designates a ‘Class’ rank based on the length of the vessels (Table 9).

TABLE 9—USAC CLASS RANK FOR GREAT LAKES VESSELS[201]

Class	Length
I	400 feet or less
II	400 – 499 feet
III	500 – 549 feet
IV	550 – 599 feet
V	600 – 649 feet
VI	650 – 699 feet
VII	700 – 730 feet
VIII	731 – 849 feet
IX	850 – 949 feet
X	950 – 1099 feet

Table 10 provides a brief description the Great Lakes “Laker” Fleet.

[201] Greenwood’s Guide to Great Lakes Shipping, 2015, Harbor House Publishers: Boynce, Michigan.

TABLE 10—THE U.S. GREAT LAKES 'LAKER' FLEET[202]

Class	Vessel Name	Owner	Built	Length (Feet)	Beam (Feet)	Mid-Summer Draft (Feet)	Mid-Summer Capacity (Tons)	Estimated Practical Capacity (Tons)	Likely Cargo	McArthur – sized
Class VI	Adam E. Cornelius	American Steamship	1973	680	78	28.58	29,200	29,108	iron ore , coal, stone, limestone, grain	No
Class X	American Century	American Steamship	1981	1,000	105	34.08	80,900	64,223	Coal, stone, iron ore, Loads coal at Midwest Energy Resources	No
Class V	American Courage	American Steamship	1979	636	68	28.00	24,300	24,300	iron ore, coal, limestone, sand, grain	Yes
Class X	American Integrity	American Steamship	1978	1,000	105	34.08	80,900	64,223	Coal, iron, stone. Two Harbors to Zug Island, Midwestern Energy Resources	No
Class VII	American Mariner	American Steamship	1980	730	78	30.92	37,300	34,099	iron ore , coal, limestone, grain	No
Class X	American Spirit	American Steamship	1978	1,004	105	28.92	62,400	61,131	iron ore, coal, stone	No
Class VIII	American Valor	American Steamship	1974	767	70	27.00	26,200	26,200	iron ore , coal, limestone, grain	Yes
Class VII	American Victory	American Steamship	1942	730	75	39.25	26,700	12,481	iron ore , coal, stone, limestone, grain	Yes
Class VIII	Arthur M. Anderson	Great Lakes Fleet	1952	767	70	27.00	25,300	25,300	iron ore, coal, limestone, salt, stone	Yes
Class V	Buffalo	American Steamship	1978	635	68	27.33	24,300	24,300	Iron ore, coal, limestone, gypsum	Yes

[202] The information herein comes primarily from the following sources: Lake Carriers Association (http://www.lcaships.com/members/), the web pages of the vessel owners, and Boat Nerd (http://www.boatnerd.com/).

Class	Vessel Name	Owner	Built	Length (Feet)	Beam (Feet)	Mid-Summer Draft (Feet)	Mid-Summer Capacity (Tons)	Estimated Practical Capacity (Tons)	Likely Cargo	McArthur – sized
Class X	Burns Harbor	American Steamship	1980	1,000	105	34.08	80,900	64,223	Almost exclusively Superior to Indiana Harbor or Burns Harbor	No
Class V	Calumet	Grand River Navigation	1929	630	68	26.00	19,650	19,650	limestone, stone, aggregates, coal, sand, and salt	Yes
Class VIII	Cason J. Callaway	Great Lakes Fleet	1952	767	70	27.00	25,300	25,300	iron ore, coal, limestone, salt, stone	Yes
Class VII	Defiance / Ashtabula	Grand River Navigation	1982	702	78		30,700	30,700	iron ore, stone, sand	No
Class VI	Dorothy Ann / Pathfinder	Interlake Steamship Co.	1953	699	70	26.25	26,700	26,700	mainly grain, some iron ore, stone	Yes
Class X	Edgar B. Speer	Great Lakes Fleet	1980	1,004	105	32.08	73,700	62,879	iron ore only and only to Gary, IN and Conneaut, OH	No
Class VII	Edward L. Ryerson (not self-unloading)	Central Marine Logistics	1959	730	75	28.33	27,500	27,500	iron ore for Dofasco as it is not self-unloading; Superior to Hamilton	Yes
Class X	Edwin H. Gott	Great Lakes Fleet	1978	1,004	105	32.08	74,100	63,279	iron ore only and only to Gary, IN and Conneaut, OH	No
Class V	Great Republic	Great Lakes Fleet	1981	635	68	28.33	25,600	25,600	iron ore, stone, coal, it was built to go on the Cuyahoga River	Yes
Class VII	H. Lee White	American Steamship	1974	704	78	30.63	35,400	32,787	iron ore , coal, limestone, grain	No
Class VI	Herbert C. Jackson	Interlake Steamship Co.	1959	690	75	27.71	24,800	24,800	Grain, coal, iron ore, stone	Yes

Class	Vessel Name	Owner	Built	Length (Feet)	Beam (Feet)	Mid-Summer Draft (Feet)	Mid-Summer Capacity (Tons)	Estimated Practical Capacity (Tons)	Likely Cargo	McArthur – sized
Class VIII	Hon. James L Oberstar	Interlake Steamship Co.	1959	806	75	28.50	31,000	31,000	iron ore, stone, coal	No
Class X	Indiana Harbor	American Steamship	1979	1,000	105	34.08	80,900	64,223	Iron ore, stone, coal	No
Class X	James R. Barker	Interlake Steamship Co.	1976	1,004	105	29.08	63,300	61,547	iron ore, coal	No
Class VIII	John G. Munson	Great Lakes Fleet	1952	768	72	27.33	25,550	25,550	iron ore, coal, limestone, salt, stone	No
Class VI	John J. Boland	American Steamship	1973	680	78	30.58	34,000	31,611	iron ore , coal, stone, limestone, grain	No
Class VIII	John Sherwin	Interlake Steamship Co.	1957	806	75		35,280	35,280	it is not self-unloading; grain storage only	No
Class VII	Joseph L. Block	Central Marine Logistics	1976	728	78	30.92	37,200	34,018	iron ore, stone, coal	No
Class VII	Joseph Thompson Jr. / Joseph Thompson	VanEnkevort Tug & Barge	1944	707	72	27.33	21,200	21,200	stone, aggregates, limestone and coal	Yes
Class VIII	Joyce Vanenkevort / Great Lakes Trader	VanEnkevort Tug & Barge	2000	845	78	30.83	39,600	35,214	iron ore, stone	No
Class VIII	Kaye E. Barker	Interlake Steamship Co.	1952	767	70	27.00	25,900	25,900	iron ore, coal, stone	Yes
Class VIII	Ken Boothe St / Lakes Contender	American Steamship	2012	740	78	30.00	38,500	36,456	iron ore , coal, limestone, grain	No
Class VIII	Lee A. Tregurtha	Interlake Steamship Co.	1942	826	75	28.08	29,300	29,300	iron ore, coal, stone	No
Class V	Manistee	Grand River Navigation	1943	621	60	24.50	14,900	14,900	stone, sand, salt, limestone and coal	Yes
Class V	Manitowoc	Grand River Navigation	1973	630	68	26.00	19,650	19,650	iron ore, stone and coal	Yes

Class	Vessel Name	Owner	Built	Length (Feet)	Beam (Feet)	Mid-Summer Draft (Feet)	Mid-Summer Capacity (Tons)	Estimated Practical Capacity (Tons)	Likely Cargo	McArthur – sized
Class X	Mesabi Miner	Interlake Steamship Co.	1977	1,004	105	29.08	63,300	61,547	iron ore, coal	No
Class VII	Olive L. Moore / Lewis J. Kuber	Grand River Navigation	1952	728	70	26.92	22,300	22,300	stone, aggregates, limestone and coal	Yes
Class X	Paul R. Tregurtha	Interlake Steamship Co.	1981	1,014	105	30.08	68,000	63,089	iron ore, coal	No
Class VIII	Philip R. Clarke	Great Lakes Fleet	1951	767	70	27.00	25,300	25,300	Iron ore, salt, stone, coal	Yes
Class X	Presque Isle	Great Lakes Fleet	1972	1,000	105	28.58	57,500	57,261	iron ore, coal, stone	No
Class IX	Roger Blough	Great Lakes Fleet	1968	858	105	27.92	43,900	43,900	iron ore, limestone, stone	No
Class V	Sam Laud	American Steamship	1975	635	68	28.00	24,300	24,300	Iron ore, coal, limestone, stone	Yes
Class VIII	St. Clair	American Steamship	1975	770	92	30.08	44,800	42,442	iron ore, coal, limestone, grain, stone	No
Class X	Stewart J. Cort	Interlake Steamship Co.	1972	1,000	105	27.92	58,000	58,000	iron ore mainly Superior to Burns Harbor due to boat configuration	No
Class II	Undaunted / Pere Marquette 41	Pere Marquette Shipping	1940	494	58	19.50	5,750	5,750	mainly stone, other various	Yes
Class VIII	Victory / James L. Kuber	Grand River Navigation	1953	807	70	27.00	25,500	25,500	iron ore, stone, aggregates, limestone and coal	No
Class X	Walter J. McCarthy Jr.	American Steamship	1977	1,000	105	34.08	80,900	64,223	iron ore , coal, limestone, grain	No
Class VI	Wilfred Sykes	Central Marine Logistics	1949	678	70	27.67	21,500	21,500	iron ore, limestone, coal, stone	Yes

APPENDIX D: SELECTED PRODUCTS MADE OUT OF STEEL

The following products are likely made, in part or in whole, with steel produced at one or more of the integrated steel mills discussed in this report.[203]

Agricultural Equipment
Air Conditioners
Air Ducts
Automotive [Trailers & Vehicles]
Automotive Parts
Bicycles – Bikes
Cans – Lids – Crown Corks
Chains
Chimneys – Chimney Caps
Chutes
Cladding – Roofing
Cranes
Cutlery
Doors – Gates – Windows
Electric Cables + Accessories
Electric Equipment
Elevators
Fencing
Fire Fighting Equipment
Furnaces – Incinerators
Furniture
Grilles
Hardware – Tools
Household Appliances
Kitchen Sinks
Kitchens
Kitchenware
Motors – Engines
Ovens – Burners – Stoves
Pumps
Radiators For Heating
Railway & Train
Ropes – Stranded Wire – Cables
Safes
Transformers
Trolleys – Handcarts
Tires – Steel Reinforced
Valves – Fittings
Water Coolers
Water Heaters

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203 Mesteel, "Fabricated Steel, and Products Made Out of Steel," at http://www.mesteel.com/cgi-bin/w3-msql/goto.htm?url=http://www.mesteel.com/products/fabricatedsteelproducts.htm, accessed March 24, 2015.

APPENDIX E: IMPACTED NAICS CODES

TABLE 11—NAICS CODES IMPACTED BY SCENARIO

NAICS Code	Industry	Anticipated Production Levels
212210	Iron ore mining	See Table 3
327215	Glass product manufacturing made of purchased glass	20.0%
331110	Iron and steel mills and ferroalloy manufacturing[204]	See Table 4
331221	Rolled steel shape manufacturing	See Table 4
331513	Steel foundries	See Table 4
332111	Iron and steel forging	See Table 4
332322	Sheet metal work manufacturing	50.0%
332510	Hardware manufacturing	0.0%
332613	Spring manufacturing	0.0%
332618	Other fabricated wire product manufacturing	0.0%
333111	Farm machinery and equipment manufacturing	0.0%
333120	Construction machinery manufacturing	0.0%
333131	Mining machinery and equipment manufacturing	0.0%
333132	Oil and gas field equipment machinery and equipment manufacturing	0.0%
333414	Heating equipment	50.0%
333415	Air conditioning and warm air heating equipment and commercial	50.0%
333924	Industrial truck, tractor, trailer, and stacker machinery manufacturing	0.0%
334290	Other communications equipment manufacturing	33.3%
334416	Capacitor, resistor, coil, transformer, and other inductor manufacturing	80.0%
334512	Automatic environmental control manufacturing for residential, commercial	50.0%
335210	Small electrical appliance manufacturing	0.0%
335221	Household cooking appliance manufacturing	0.0%
335222	Household refrigerator and home freezer manufacturing	0.0%
335224	Household laundry equipment manufacturing	0.0%
335228	Other major appliance manufacturing	0.0%
336111	Automobile manufacturing	0.0%
336112	Light truck and utility vehicle manufacturing	0.0%
336120	Heavy duty truck manufacturing	0.0%
336211	Motor vehicle body manufacturing	0.0%
336212	Truck trailer manufacturing	0.0%
336212	Truck Trailer Manufacturing	0.0%
336214	Travel Trailer and Camper Manufacturer	0.0%
336310	Motor vehicle gasoline engine and engine parts manufacturing	0.0%
336320	Motor vehicle electrical and electronic equipment manufacturing	10.0%
336330	Motor vehicle steering and suspension components	10.0%
336340	Motor vehicle brake system manufacturing	10.0%
336350	Motor vehicle transmission and power train parts manufacturing	0.0%
336360	Motor vehicle seating and interior trim manufacturing	0.0%
336370	Motor vehicle metal stamping	0.0%
336390	Other motor vehicle parts manufacturing	50.0%
336510	Railroad rolling stock manufacturing	50.0%
336999	All other transportation equipment manufacturing	0.0%
337124	Metal household furniture manufacturing	0.0%

[204] Integrated steel mills only.

NAICS Code	Industry	Anticipated Production Levels
423110	Automobile and other motor vehicle merchant wholesalers	10.0%
423120	Motor vehicle supplies and new parts merchant wholesalers	25.0%
423620	Household appliances, electric housewares, and consumer electronics wholesale	50.0%
423810	Construction and mining machinery and equipment merchant wholesalers	50.0%
423820	Farm and garden machinery and equipment merchant wholesalers	25.0%
423830	Industrial machinery and equipment merchant wholesalers	10.0%
441110	New car dealers	10.0%
441120	Used car dealers	120.0%
441310	Automotive parts and accessories stores	50.0%
483113	Coastal and Great Lakes Freight Transportation	TBD
488320	Marine cargo handling	TBD

APPENDIX F: LIGHTERING CALCULATIONS

Based on the redacted assumptions, OCIA-NISAC estimates that a Laker can make a round trip from Two Harbors, Minnesota to Gary, Indiana and return in about 5.48 days. Over the course of 26 days, the Laker could load at Two Harbors, Minnesota and unloaded at Gary, Indiana 5 times. Therefore, the 13 1000 footers could, collectively, unload 65 times at Gary, Indiana.

Over the course of 26 days, OCIA-NISAC estimates that a Laker could go from Sault Ste. Marie, MI to Gary, IN and unload 7 times. The reason for more unloadings is the that travel time through the Soo Locks and to and from Two Harbors, MN to Sault Ste. Marie, MI is longer than the time it would take to lighter a Laker. However, the constraint is that only 4 One Thousand Footers would be able to make these trips. Therefore, the 4 One Thousand Footers could, collectively, unload 28 times at Gary, IN.

The number of unloadings under normal conditions is estimated to be 65. The number of lightering unloadings is estimated to be 28, which is about 43 percent of the normal unloadings. The weather constraints outlined in the assumptions means that lightering could only take place about two-thirds of the time. Therefore, the amount of iron ore that could be lightered is 29 percent (43 percent multiplied by 66 percent).[205]

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[205] The actual equation is, .431*.663 that does equals .29.

Time in hours between major ports	TWO HARBORS	TORONTO	TOLEDO	THUNDER BAY	SOO LOCKS	SILVER BAY	QUEBEC CITY	PORT WELLER	PORT HURON	PORT COLBORNE	MONTREAL	MILWAUKEE	MARQUETTE	MACKINAW BRIDGE	LORAIN	KEWEENAW	HOLLAND	GREEN BAY	GRAND HAVEN	ESCANABA	DULUTH	DETROIT	CONNEAUT	CLEVELAND	CHICAGO-GARY	BUFFALO
ASHTABULA	59	17	8	51	34	55	58	15	16	7	45	49	45	33	5	55	52	42	50	43	59	10	1	4	57	7
BUFFALO	66	11	15	58	41	62	53	10	23	2	40	56	52	40	13	62	58	49	57	50	66	17	3	5	64	
CHICAGO/GARY	54	74	53	46	29	50	110	72	41	64	97	7	40	24	54	46	7	18	12	19	54	47	58	55		
CLEVELAND	56	19	6	49	32	53	60	17	14	9	47	47	43	31	1	53	49	40	48	41	57	8				
CONNEAUT	60	16	9	52	35	56	57	14	17	6	44	50	46	34	6	56	52	43	51	44	60	11				
DETROIT	49	27	6	41	24	45	63	25	6	17	50	39	35	23	7	47	41	32	40	33	55					
DULUTH	2	77	56	13	25	4	118	73	44	65	105	48	36	32	56	10	50	41	49	42						
ESCANABA	40	58	39	32	15	36	96	58	27	50	83	13	26	10	40	32	8									
GRAND HAVEN	50	68	46	42	25	46	103	65	34	57	90	6	36	17	47	39	2									
GREEN BAY	43	59	38	35	18	39	95	57	26	49	82	12	29	9	39	31	13									
HOLLAND	50	68	47	42	25	46	104	66	35	58	91		36	18	48	40	2									
COPPER HBR.	10	67	46	7	15	10	110	54	34	46	97	38	9	22	52											
LORAIN	56	20	5	48	31	52	61	18	13	10	48	46	42	30												
MACKINAW BRIDGE	27	50	29	34	7	28	86	48	17	40	73	16	18													
MARQUETTE	16	63	42	11	11	16	98	60	30	52	85	34														
MILWAUKEE	48	66	45	40	23	44	102	64	33	56	89															
MONTREAL	96	20	53	88	71	92	13	30	66	38																
PORT COLBORNE	66	10	15	58	41	62	53	8	23																	
PORT HURON	44	33	12	36	19	40	69	31																		
PORT WELLER	74	2	23	66	49	70	45																			
QUEBEC CITY	109	43	68	101	84	105																				
SILVER BAY		73	52	10	21																					
SOO LOCKS	25	52	31	17																						
THUNDER BAY		69	47																							
TOLEDO	55	25																								
TORONTO	76																									

Times on this page are an estimate based on:

- Welland Canal estimated at 8 hours.
- Soo Locks estimated at 30 minutes.
- Detroit, St. Clair and St. Marys Rivers estimated at restricted speed.
- Estimates are based on open lake speed of 15 mph.
- Modern vessels may average between 12 mph and 18+mph in open water.
- Estimates exclude Fuel Stops and Abnormal Locks Delays.

FIGURE 33—GREAT LAKES AND SAINT LAWRENCE SEAWAY TRAVEL TIMES[206]

206 Boat Nerd, "Great Lakes and Saint Lawrence Seaway Travel Times" at http://boatnerd.com/facts-figures/travel_times-lakes.htm, accessed March 2, 2015.

APPENDIX G: ANALYSIS OF THE IMPACT OF A DISRUPTION IN COAL SHIPMENTS TO MICHIGAN ELECTRIC POWER GENERATION

BACKGROUND

Two types of coal are transported on the Great Lakes. The significantly smaller portion is metallurgical or coking coal, which is an essential ingredient in steel manufacturing. Most of the coal shipped on the Great Lakes is thermal coal, which is used for electric power generation, particularly in Michigan. The coal used in Michigan's coal-fueled power plants mixes western coal, which has low sulfur content, with eastern coal, which has a higher heat content.[207] The Western coal is railed from the Powder River Basin in Wyoming and Montana to DTE Energy's Midwest Energy Resource Co. docks at the Port of Duluth-Superior. The coal then moves, via a Lake Carrier, through the Soo Locks to Michigan. The Eastern coal is shipped by rail from West Virginia and the surrounding States to Michigan.

The question regarding the need for western coal results from a scenario whereby a sufficient supply of iron ore is transported, but there is no capacity to move coal by Lake Carrier.[208] Can a sufficient supply of coal be transported to Michigan via alternative routes, such as rail, or is the coal even necessary to support manufacturing production?

COAL-FIRED PLANTS IN MICHIGAN

TABLE 12—TOP COAL-FIRED POWER PLANTS IN MICHIGAN

Plant	Nameplate Capacity (MW)	Summer Capacity (MW)	2013 Summer Model Generation (MW)	2014 Electricity Generation (MWHr)
Monroe	3,280	2,930	3,090	14,572,303
J H Campbell	1,586	1,440	1,440	8,574,687
Belle River	1,395	1,284	1,233	7,564,057
St Clair	1,547	1,374	1,367	5,339,461
Trenton Channel	776	713	700	2,524,496
River Rouge	651	527	519	2,125,977
Dan E Karn	544	515	515	2,011,851
Presque Isle	450	344	344	1,887,006
B C Cobb	313	312	312	1,862,030
J R Whiting	345	325	323	1,813,193
J C Weadock	313	310	310	1,705,975
Eckert Station	375	299	180	547,163
TES Filer City Station	70	60	60	368,881

Coal is the base load fuel for Michigan's electric power generation, meaning that the coal-fired electric power generation provides electric power to meet the minimum level of electric power demand. Table 12 shows Michigan's largest coal-fired power plants. Most of the generation facilities are located in the southeastern part of

207 Union of Concerned Scientists, "How Coal Works," www.ucsusa.org/clean_energy/coalvswind/brief_coal.html#.VP8whGO9F5o, accessed March 11, 2015.
208 The analysis in Appendix F was conducted by Los Alamos National Laboratory in support of OCIA-NISAC.

Michigan where these facilities supply electric power in the area of significant automobile manufacturing.[209] The table includes the nameplate or rated capacity of the generator, the summer capacity, the estimate of generation in the 2013 summer-peak model, and the total 2014-generation for each plant.[210] The summer capacity is essentially equivalent to the 2013 summer model generation, which shows that these generation facilities are for base load generation, as they are in almost constant use.

Coal-fired plants account for nearly 40 percent of Michigan's summer generation capacity and 54 percent of Michigan's net annual electricity generation.[211,212] An unexpected closure of the Poe Lock could, similar to the disruption of the iron ore trade, disrupt the coal trade. In many cases, the same Lakers used to move iron ore also move coal so the transport of both would stop. However, if iron ore cannot be moved to the Great Lakes steel mills, then the coal likely is not a critical issue, as electric power demand from Michigan's manufacturing base would be severely diminished. The coal is used as a fuel source for the electric power generators that most directly support Michigan's manufacturing base. The reduction in electric power demand resulting from the Poe Lock closure scenario implies a reduced need for coal to maintain reliable electricity in Michigan.

The reduced demand for coal is borne out by an analysis of the 2009 recession. Table 13 shows a comparison of GDP change, from 2008 to 2009 and from 2009 to 2010, to electric power demand change. This loss of generation is roughly equivalent to the generation provided by Monroe, which is the largest generation facility (see Table 12). While the OCIA did not calculate an equivalent GDP impact for the Soo Locks scenario, the decrease in annual automobile sales is informative. From 2008 to 2009, the decline in automobile sales was 21.2 percent. Under the Poe Lock closure scenario, automotive sales would likely decline by about 75 percent. [213,214] The corresponding decrease in electric power demand may be roughly equivalent to the output of the next three largest generators- JH Campbell, Belle River, and St. Clair.

TABLE 13—CHANGE IN MICHIGAN GDP AND ELECTRIC POWER DEMAND FROM 2008-2010

Period	Michigan GDP Change[215]	Michigan Electric Power Demand Change[216]
2008-2009	-8.3%	-10.3%
2009-2010	+5.3%	+8.2%

ANALYSIS 1: MOVING COAL BY RAIL

Coal makes up about a quarter of the shipments going through the Soo Locks.[217] The majority of western coal is sent to the Ports of Duluth-Superior, where it is loaded on ships and sent through the Soo Locks (see Figure 34). A smaller portion is railed to Chicago, and then shipped up-bound to coal-fired generators in Michigan.

OCIA-NISAC used the OCIA-NISAC R-NAS model to model potential impacts to the rail industry. The rail routes displayed in Figure 34 only include segments with more than 24 cars per day.

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209 Technically, electric power generated by an individual station or multiple stations does not directly supply industrial needs. Rather, the generation is added to the bulk power system and is directed by Balancing Authorities and local distribution companies to specific end-users. However, the loss of significant amounts of generation in an area of high demand lower the reliability levels and makes the area more susceptible to cascading failures.
210 Capacities from U.S. Energy Information Administration (EIA)-860; total generation from EIA-923.
211 Energy Information Administration, "EIA-860, Annual Electric Generator Report," www.eia.gov/electricity/data/eia860/, accessed March 11, 2015.
212 Energy Information Administration, "Michigan State Profile and Energy Estimates," www.eia.gov/state/?sid=MI, accessed March 11, 2015.
213 Federal Reserve Bank of St. Louis, "Light Weight Vehicle Sales: Autos & Light Trucks," at https://research.stlouisfed.org/fred2/series/ALTSALES/#, accessed March 27, 2015.
214 Some automotive sales would occur in the first one-third of the month and there may be some foreign manufacturers who continue to produce cars.
215 Federal Reserve Bank of St. Louis, "Real Total Gross Domestic Product by State for Michigan," at http://research.stlouisfed.org/fred2/series/MIRGSP#, accessed March 27, 2015.
216 US Energy Information Administration, "Michigan Electricity Profile: 2012, Table 10" at http://www.eia.gov/electricity/state/michigan/, accessed March 27, 2015.
217 Lake Carriers Association, "U.S. Flag Shipments of Dry-Bulk Cargos on the Great Lakes: Calendar Years 2008-2013 and 5-Year Average," at www.lcaships.com/wp-content/uploads/2014/07/60005_60005-LCA_p1-4.pdf, accessed March 15, 2015.

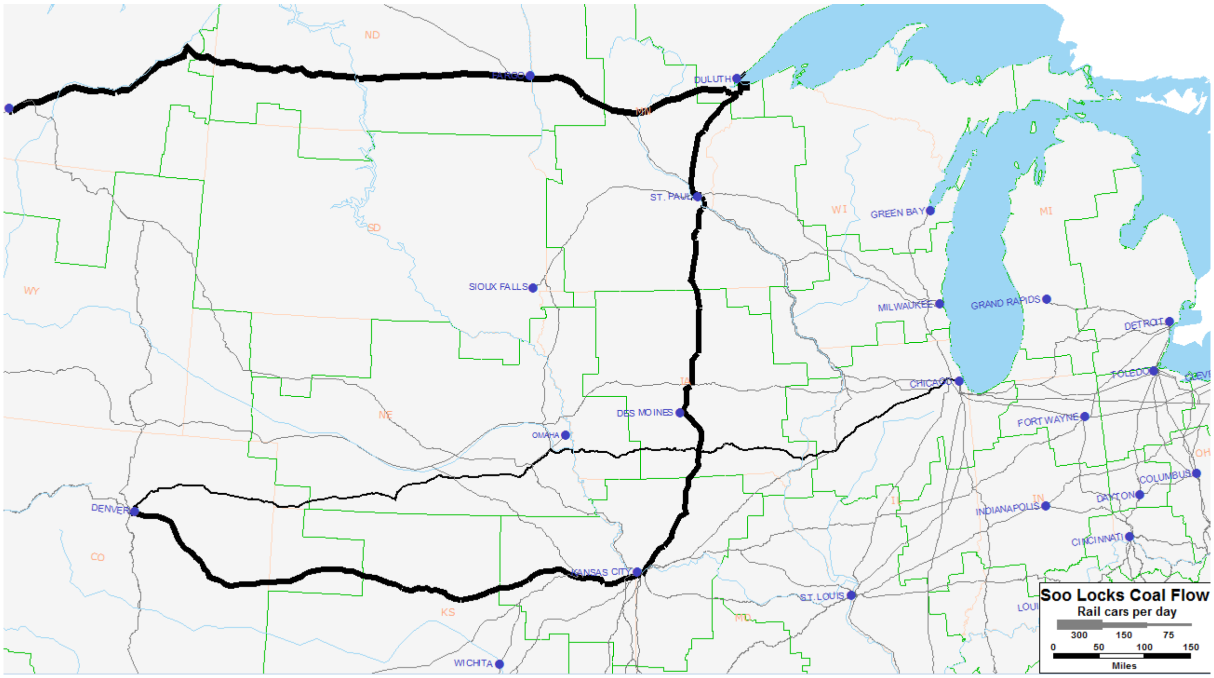

FIGURE 34—RAIL TRAFFIC FOR COAL PRIOR TO A POE LOCK SCENARIO CLOSURE

OCIA-NISAC estimated the impact to the rail network after a Poe Lock closure scenario. Figure 35 shows flow of western coal on the rail network after an unanticipated closure, using the same scale for line thickness as Figure 34 The thickest lines in both figures represent flow volumes of about 380 cars per day, equivalent to about 4 unit trains. The disruption scenario shows the coal flowing through Chicago and then on to Michigan and Ohio.

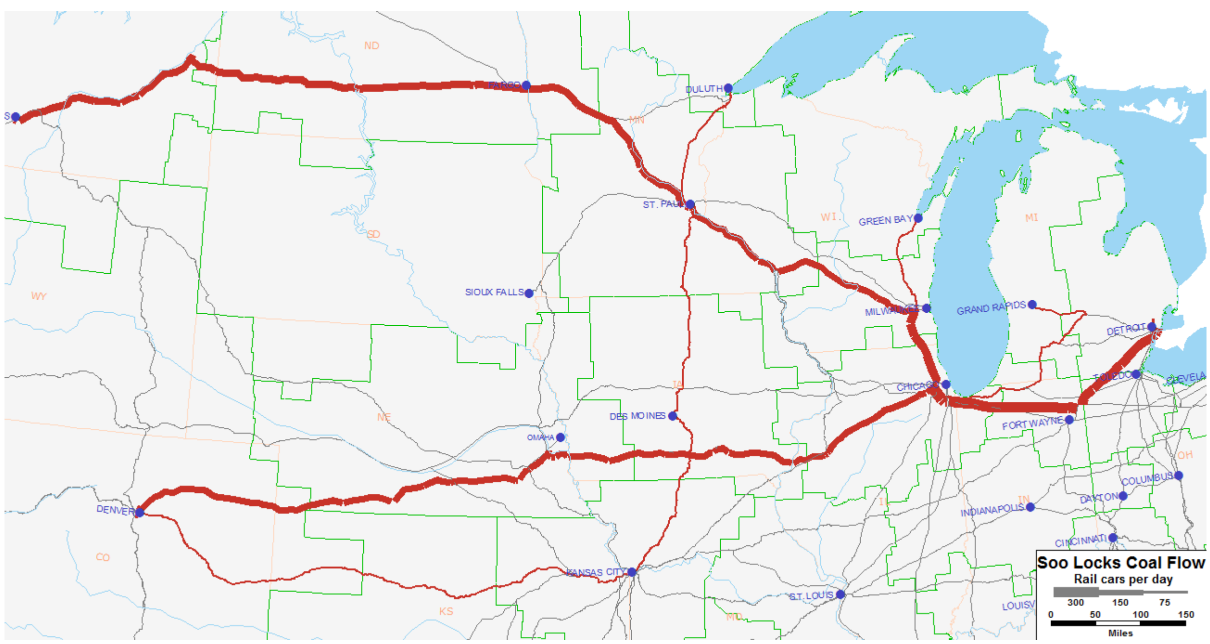

FIGURE 35—SOO LOCKS RAIL TRAFFIC FOR COAL DURING POE LOCK SCENARIO CLOSURE

OCIA-NISAC estimates that there is about a 41 percent increase in railcar-miles after the disruption, based on the additional mileage necessary to move the coal to eastern Michigan instead of the Port of Duluth-Superior.[218] However, because of the decrease in coal shipments (see Figure 36) due to the closing of some coal-fired generation facilities and the increased transportation of crude oil that has usurped coal shipments, the infrastructure likely exists to move the 4 unit trains a day necessary to provide Michigan with Powder River Basin coal.[219,220] Further, an industry executive confirmed that capacity exists to move a limited number of additional trains. Most of this coal is already transported partway by rail; in the post-disruption scenario, it must now travel longer distances, across or around Chicago by rail, to reach its destination in Michigan.[221]

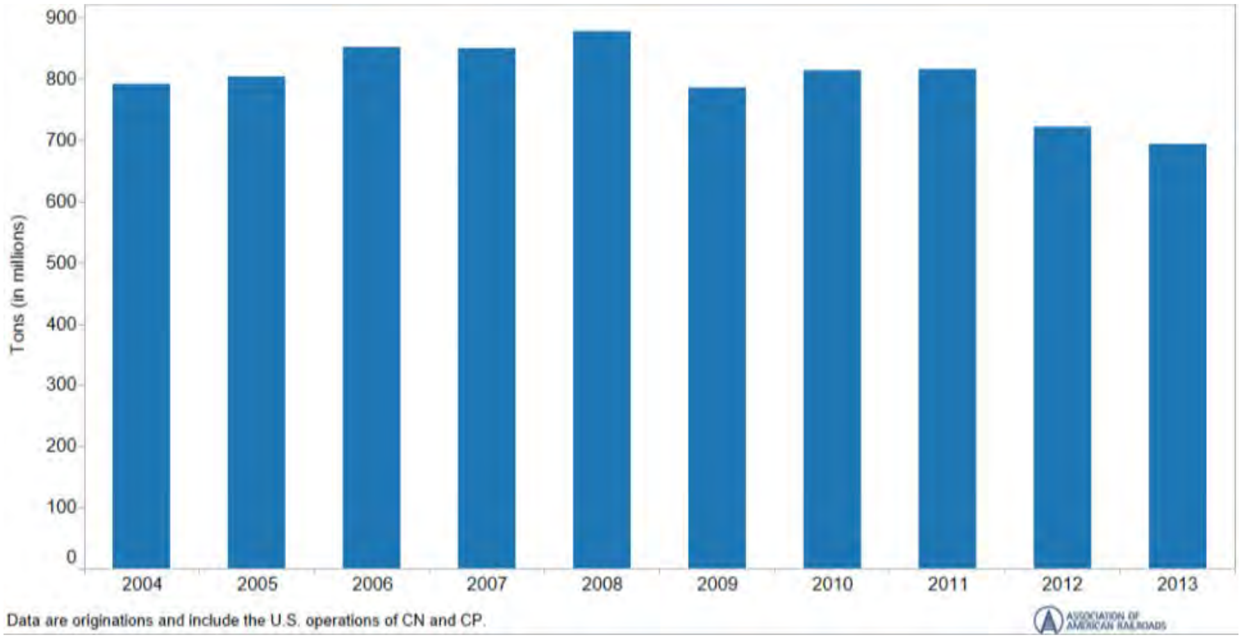

FIGURE 36—ANNUAL SHIPMENTS OF COAL (MILLIONS OF TONS)[222]

ANALYSIS 2: CONTINGENCY ANALYSIS OF MICHIGAN'S BULK ELECTRIC POWER SYSTEM

OCIA-NISAC's contingency study examines a specific scenario whereby all coal-fired generation in Table 12 is taken offline because of an inability to transport coal, but iron ore is available and steel production continues. This is to address the question of whether a lightering policy needs to consider the shipment of coal. Because steel production continues, automobile production is not impacted and an adequate supply of electricity is required for Michigan manufacturers. The sum of the lost generation in Table 12 totals 9.2 gigawatts (GW) in the spring and 10.4 GW in the summer, which is roughly equivalent to the amount of power needed to power 8 million homes.

OCIA-NISAC analysts determined that there are three potential sources of generation available to replace the lost coal-fired generation. First, in the summer-peaking model, which analyzes the ability of the bulk power system to supply adequate electricity for the hour of highest demand, the "peak hour" or "peak conditions," there is over 5 GW of available excess generation capacity at other facilities in Michigan, mostly natural gas-fired plants. Second, the Midwest Independent System Operator (MISO), which is responsible for coordinating the bulk power system

218 For the purposes of analysis, it is assumed that once a shipment is interrupted by the Soo Locks it can only use rail to reach its final destination, it will not be routed to an alternative port and then send on water.
219 Wall Street Journal, "Surge in Rail Shipments of Oil Sidetracks Other Industries," on March 13, 2014, www.wsj.com/articles/SB10001424052702304914904579437680173044774, accessed March 16, 2015.
220 A unit train, also called a block train or a trainload service, is a train in which all cars carry the same commodity and is shipped from the same origin to the same destination, without being split up or stored *en route*.
221 This analysis only considers physical and logistical constraints, not potential cost differentials that may affect business decisions.
222 U) Association of American Railroads, "Annual Rail Traffic Data: Coal," at www.aar.org/data-center/rail-traffic-data , accessed March 16, 2015.

in much of the Midwest, has a reserve capacity of between 5 and 15 GW of excess generation available. The higher range of excess generation assumes that temperatures and generator outage rates are normal for the summer, while the lower range of excess generation assumes that temperatures are high and generator outage rates, called forced outage rates, match historical highs. That reserve capacity is composed of on-hand excess generation, net firm imports, behind-the-meter generation, and demand response.[223,224,225,226,227] Finally, the Ontario Independent Electricity System Operator (IESO), the equivalent to MISO in Ontario, has between 6 and 12 GW of excess generation capacity at the time of its summer peak customer demand.[228,229]

Based on the availability of between 11 and 27 GW of excess generation capacity in MISO and IESO, there is adequate generation available in spring and summer to offset the loss of coal-fired generation. However, this supplemental generation may or may not be available for extended periods. The continued use of these generators for extended periods would likely increase the risk of forced outages of these facilities. Generating companies may not be willing to run their generation plants if, by doing so, it would put the plants at risk for unplanned outages. Maintenance schedules for these plants are not known to OCIA-NISAC.

While there appears to be sufficient generation available to compensate for the loss of coal-fired plants, this does not imply that the transmission system is capable of moving this power to the areas where it is needed. The contingency analysis determines whether the transmission system can withstand the transfer of this power into Michigan without experiencing overloaded transmission lines or areas of low voltage or voltage collapse. Indiscriminate shifting of large quantities of generation in an electric power flow model can lead to instabilities and, ultimately, to loss of electric power in an area. However, the contingency analysis does not consider reducing load, meaning decreasing electric power demand, either by executing interruptible contracts, through other load management programs, such as air conditioner interruption programs, or by requests for customers to conserve electric power, activities that may all take place if generation reserves fall to low levels.[230,231]

Preliminary analysis indicated that other electric power generators in Michigan and neighboring regions could cover the generation shortfall of 9.2 GW in the spring. The shift in generation was accomplished without resulting in overloaded transmission lines or regions of low voltage. Approximately half this generation was picked up within the State of Michigan, while the other half came from utilities in Indiana, Illinois, Ohio, and Canada.

The contingency analysis indicated that the generation shortfall of 10.4 GW in the summer could not be covered by other electric power generators in Michigan and neighboring regions without stressing the system. The model suggested other generation in Michigan or the surrounding States or Provinces could provide about 72 percent of the required power without causing any overloaded transmission lines or regions of low voltage. However, attempting to move the remaining 28 percent of typical summertime requirements caused the model to fail.[232] It is likely that, under summer peak conditions, utilities might have to exercise interruptible contracts and demand response, or even impose rolling blackouts, to make up for the nearly 3 GW shortfall in generation. This would only be necessary for periods of very high customer demand, which generally occurs for a few hours per day and

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223 On-hand excess generation is generation remaining after demand has been met. Operators have scheduled it as available before the time of the summer peak. It is nameplate minus derates minus inoperables minus scheduled outages.

224 Net firm imports are the total expected firm (contracted) power flow into the MISO region (from other NERC entities – PJM, SERC, SPP and IESO) at the time of the summer peak.

225 Behind the meter generations is generation operated under the control of the customer (hence behind the meter; i.e., the customer's electric meter).

226 Demand response is the ability of a "utility" (or "marketing participant", balancing authority, or anyone who sends electricity to customers) to reduce its electric consumption in response to an instruction received from an Independent System Operator.

227 Midwest Independent System Operator, "MISO 2014 Summer Resource Assessment," www.misoenergy.org/Library/Repository/Study/Seasonal%20Assessments/2014%20Summer%20Resource%20Assessment.pdf, accessed March 11, 2015.

228 Independent Electricity System Operator, "Ontario's Electricity System," www.ieso.ca/ontarioenergymap/index.html, accessed March 11, 2015. Generation capacity equals 33,771 MW. Summer peak demand was 27,005 on August 1, 2006, but only 21,363 MW in 2014. www.ieso.ca/Pages/Power-Data/2014-Electricity-Production-Consumption-and-Price-Data.aspx, accessed March 16, 2015.

229 The bulk power grid in Canada, the United States, and parts of Mexico is operated without respect to political boundaries. The North American Electric Reliability Corporation is responsible for the bulk power grid reliability across the three countries and electric power moves across the borders as needed.

230 Some utility customers agree to have their electric power delivery terminated, if needed, in order to reduce electric power demand when the system is unstable. In return, the customers are charged lower rates.

231 MISO could reduce demand by executing interruptible contracts. In MISO, there were at least 4.5 GW of interruptible contracts in the summer of 2014. Load-reduction activities begin if reserves drop below 2,400 MW. See "MISO 2014 Summer Resource Assessment," www.misoenergy.org/Library/Repository/Study/Seasonal%20Assessments/2014%20Summer%20Resource%20Assessment.pdf, accessed March 11, 2015.

232 More extensive analysis would be required to determine the cause of the divergence and whether it is due to numerical limitations of the modelling software or physical limitations of the electrical system in wheeling this much power into Michigan.

for a few days during the year. This result suggests that it would be prudent to keep at least 3 GW of the 10.4-GW coal-fired generation that was lost due to the closing of the Soo Locks, in service for summer peak. This point will be addressed further in Analysis 3.

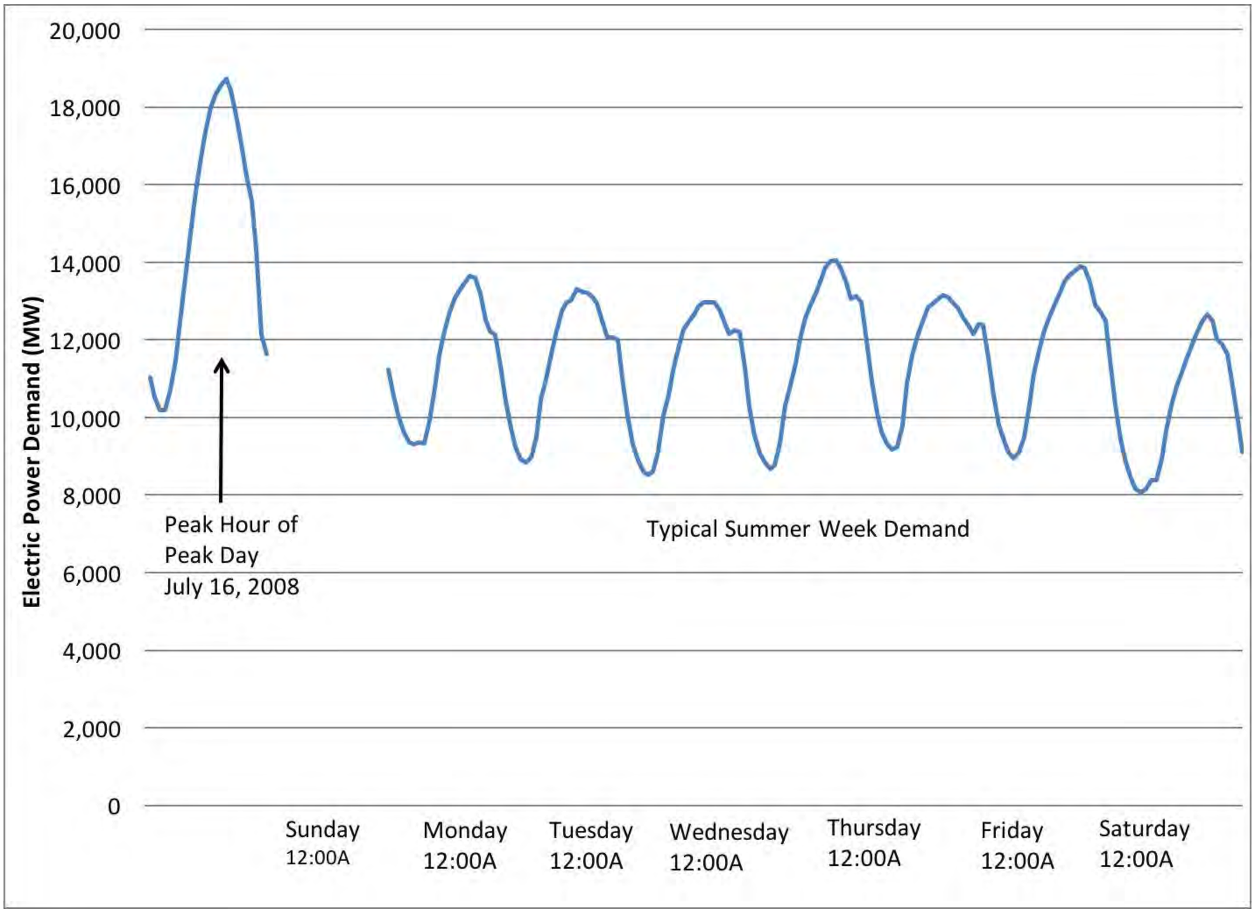

FIGURE 37—HOURLY LOAD CURVES FOR THE PEAK SUMMER DAY WITH THE HIGHEST ELECTRICAL USAGE AND DAILY LOAD CURVES DURING A REPRESENTATIVE SUMMER WEEK IN MICHIGAN IN 2008.

It should be noted that it is unlikely that MISO, or any regional operator, would actually operate the transmission system as suggested by the contingency model because increasing the use of other generation facilities would greatly reduce the reserve margin.[233] Without ample generation reserves, the bulk power system would be at increased risk if additional transmission or generation assets suddenly tripped out of service. However, this should only be a problem when the bulk power demand approaches its peak loading conditions, which only occurs for a limited number of hours during the year. This is demonstrated in Figure 37, where the state of Michigan's summer-peak demand of 18,700 MW, which occurred at 4:00 P.M. on July 16, 2008, is much greater than the daily peak demands that occurred during the average week that summer.[234] The daily peak loading conditions only occur for a few hours a day. It is further demonstrated in Figure 38, which depicts a load-duration curve for the Michigan utilities. The load duration curve expresses how many hours during the year that the system experiences demands above a particular value. For example, the demand in Michigan exceeded 16,000 MW for 140 hours in 2008. From the figure, the Michigan electrical system experienced demands within 2.9 GW of its yearly peak, the amount of power shortfall indicated by the earlier analysis showing that 72 percent of electric power demand could be met without stressing the system, for 155 hours in 2008.

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233 The entities responsible for the bulk power grid stability and reliability must keep a certain percentage of their generation capacity in reserve in the event of unforeseen circumstances such as plant outages, extreme weather, or other disruptions.

234 Data obtained from FERC Form 714. Demand data for Michigan is the sum of demand data for Detroit Edison and demand data for Consumers Energy. Hourly demand data for the individual utilities is not available after 2008, See FERC www.ferc.gov/docs-filing/forms/form-714/data.asp, accessed March 15, 2015.

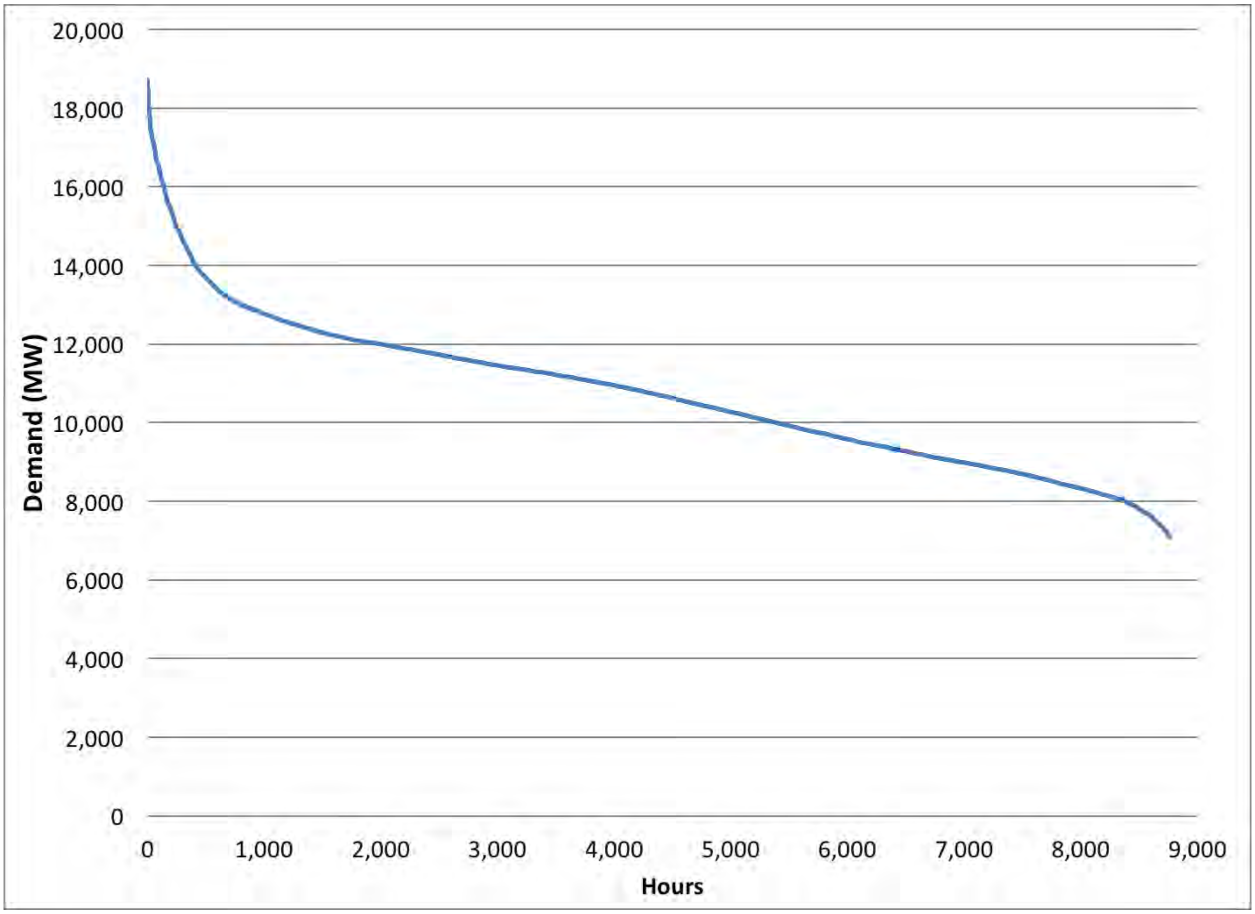

FIGURE 38—LOAD DURATION CURVE FOR MICHIGAN UTILITIES FOR THE YEAR 2008. THE LOAD DURATION CURVE EXPRESSES HOW MANY HOURS DURING THE YEAR THAT THE SYSTEM EXPERIENCED DEMANDS ABOVE A PARTICULAR VALUE.

ANALYSIS 3: RELYING ON EXISTING COAL STOCKS

Coal-fired electric power generators generally keep a 1- to 3-month stockpile of coal onsite. Table 14 shows the annual coal deliveries in 2013 to 2014 to the Power Plants identified in Table 12. Monroe, the largest coal-fired plant in Michigan, receives about 680,000 short tons of coal per month. Monroe has a port on Lake Erie, which may aid the year-round delivery of coal. Table 14 provides the information necessary to determine how much electricity can be generated by one net ton of coal. At Monroe, 1.9-megawatt hours (MWHr) of electricity is produced for every short ton of coal consumed. The average electricity production for all coal-fired plants in Michigan is about 1.8 MWHr per short-ton.

TABLE 14—COAL DELIVERED AND CONSUMED; ELECTRICITY GENERATED AT MICHIGAN COAL-FIRED PLANTS

Plant	2014			2013		
	Tons Delivered	Tons Consumed	Electricity MWHr	Tons Delivered	Tons Consumed	Electricity MWHr
Monroe	8,131,739	7,532,913	14,572,303	7,784,949	8,309,642	15,961,902
J H Campbell	5,093,476	4,764,741	8,574,687	4,225,854	4,884,102	8,591,976
Belle River*	0	4,258,122	7,564,057	0	4,262,341	7,589,031
BRSC Shared Storage*	6,804,878			6,902,859		
St Clair*	528,234	3,050,976	5,339,461	246,541	3,647,138	6,178,063
Trenton Channel	1,551,801	1,499,598	2,524,496	1,825,724	1,979,362	3,406,770
Presque Isle	1,299,897	1,248,815	1,887,006	1,326,481	1,236,463	1,882,904
Dan E Karn	1,066,546	1,136,524	2,011,851	1,381,856	1,494,265	2,544,690
J R Whiting	1,094,451	1,093,830	1,813,193	982,449	1,012,394	1,653,060
River Rouge	1,173,310	1,091,641	2,125,977	1,126,273	1,246,692	2,254,911
B C Cobb	1,031,570	1,079,788	1,862,030	902,610	1,046,423	1,783,115
J C Weadock	1,144,452	959,112	1,705,975	989,164	920,629	1,627,591
Eckert Station	388,426	365,774	547,163	408,274	358,481	508,998
TES Filer City Station	248,893	212,791	368,881	171,538	188,499	310,484
Escanaba Paper Company	102,847	48,184	81,155	110,288	47,553	79,807
T B Simon Power Plant	69,755	19,132	78,818	57,533	22,359	93,569
Wyandotte	19,533	17,770	21,984	7,188	17,552	12,255
* Belle River and St Clair share storage of coal (BRSC Shared Storage)						

In 2014, Michigan coal-fired plants produce an average of 4.26 million MWHr of electricity production per month (EIA-923 data), which corresponds to the amount of electricity that would be generated from 2.37 million short tons of coal. Therefore, the amount of coal on hand in Michigan at any given time is enough to produce about 1 to 3 months of electricity. However, at the time that the Soo Locks navigation season commences at the end of March, stocks are generally at their season lows of 1 to 2 months' worth of stock.

On average, at the end of March, the time corresponding to the Soo Locks closure scenario, there is about 4.63 million short tons of coal in stock.[235] The 4.63 million short tons of coal could generate about 8.33 MWHr using the ratio of 1.8MWHr per short ton of coal. The 8.33 MWHr of generation using the stock could produce about 2777 hours of electricity from 3 GW of electric power generation. However, the previous analysis suggested that, in a typical year, there are only 155 hours that would require 2.9 GW of additional electric power generation suggesting that the coal stocks could be maintained to meet peak conditions.

CONCLUSION OF COAL ANALYSIS

The analysis suggests that the loss of coal shipments on the Great Lakes would not cause a cessation of manufacturing in Michigan in the specific case that iron ore is shipped, but coal is not. First, there should be sufficient ability to move up to four unit trains of coal per day from the Powder River Basin to Michigan, making it likely that enough coal could be moved to Michigan to maintain electric power for manufacturing needs. Second, other existing non-coal-fired electric power generators and interruptible contracts are likely to be sufficient to cover generation shortfalls, except during peak periods during the summer. Third, there should be a 1- to 2-month supply of coal stocks remaining in Michigan at the time of the closure. By combining the second and third point, there should be sufficient reserve capacity and coal stockpiles to meet peak summer conditions. Finally, what is not

235 This is an average of the 2010-2014 after tossing out the highest and lowest figures that may be aberrant.

known is whether Michigan imports western coal due to economics or regulatory requirements or because of the physical characteristics of the generators. If the cause is economics or environmental, then logistically, it is likely fairly easy to move additional coal from West Virginia and the surrounding environs to Michigan. The movement of coal is not a necessary component of a strategy to mitigate a Soo Locks closure.

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First, and absolutely foremost, we wish to express our deep appreciation to the anonymous 'industry executives.' These people shared their time, experiences, insights, and anecdotes and were critical to the development of this report. Their honesty and forthrightness were instrumental in our ability to piece together this supply chain and understand all of its intricacies, to the extent that we have. They will have to remain anonymous as we promised them that no references would be made to the person, firm, or specific industry.

The Great Lakes, Region V, Protective Security Advisors (PSA) from the DHS Office of Infrastructure Protection, have been true partners in every sense. This report reflects the joint efforts of the PSAs and OCIA-NISAC and we thank them for their work and service.

Who knew that a senior economist at the Federal Reserve Bank of Chicago would have written a piece about a trip that he took on a Laker going through the Soo Locks? But finding that piece led us to meet the author, William Strauss, who reviewed and commented extensively on the work, directed us on avenues to consider, and introduced us to many of the industry people. Bill has been a tremendous resource and a great guide.

We wish to thank the national laboratories that support OCIA-NISAC. Los Alamos National Laboratory is primarily responsible for the analysis that led to Appendix F. Sandia National Laboratories and Professor Thomas Drennen of Hobart and William Smith Colleges ran the REMI models using the assumptions that OCIA-NISAC derived. As we stated earlier, the authors remain solely responsible for the findings.

We also extend our thank you to the OCIA Production Management Branch, who kept a keen eye for detail throughout the development of this paper and refined our writing to be as efficient, coherent, and succinct.

The report was shared with the following U.S. Government Agencies. We believe that we have incorporated all of their comments and we thank them for their assistance:

- U.S. Department of Transportation / Federal Railway Administration
- U.S. Department of Transportation / U.S. Maritime Administration: Great Lakes Gateway Office
- U.S. Department of Transportation/ Federal Highway Administration
- U.S. Department of Transportation / U.S. Maritime Administration
- U.S. Department of Transportation / Pipeline and Hazardous Materials Safety Administration
- U.S. Department of Transportation / Office of the Secretary
- U.S. Army Corps of Engineers: Great Lakes and Ohio River Division
- U.S. Army Corps of Engineers: Detroit District
- U.S. Army Corps of Engineers: Soo Field Office
- U.S. Coast Guard

The following Canadian Government Agencies reviewed the report:

- Public Safety Canada
- Industry Canada

In addition, the Saint Lawrence Seaway Development Corporation provided a review.

DHS POINT OF CONTACT

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OMB Control No.: 1670-0027
Expiration Date: 10/31/2017

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Homeland Security

National Protection and Programs Directorate

NPPD Customer Feedback Survey

Product Title:

1. Please select the partner type that best describes your organization. Select One

2. Overall, how satisfied are you with the usefulness of this product?

Very Satisfied	Somewhat Satisfied	Neither Satisfied Nor Dissatisfied	Somewhat Dissatisfied	Very Dissatisfied

3. How did you use this product in support of your mission?

- ☐ Integrated into one of my own organization's information or analytic products
- ☐ Used contents to improve my own organization's security or resiliency efforts or plans
  - If so, which efforts?
- ☐ Shared contents with government partners
  - If so, which partners?
- ☐ Shared contents with private sector partners
  - If so, which partners?
- ☐ Other (please specify)

4. Please rank this product's relevance to your mission. ***(Please portion mark comments.)***

Critical

Very Important

Somewhat Important

Not Important

N/A

5. Please rate your satisfaction with each of the following:

	Very Satisfied	Somewhat Satisfied	Somewhat Dissatisfied	Very Dissatisfied	N/A
Timeliness of product or support					
Relevance to your information needs					

6. How could this product or service be improved to increase its value to your mission? ***(Please portion mark comments.)***

To help us understand more about your organization so we can better tailor future products, please provide (OPTIONAL):

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Organization:

Contact Number:

Position:

State: Select One

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2017 Mining Tax Guide

Get the most up-to-date mining taxes information at

www.revenue.state.mn.us.

DEPARTMENT OF REVENUE

2017 Distribution of Production Tax

(Based on 2016 Production Year)

Total Production Tax — $96,516,727*

Production Tax per taxable ton – $2.659. Taxable tonnage – 33,524,393 tons.

Cities and Townships
$11,620,497
34.6 cpt

- **City and Township Mining & Conc Fund**** $1,940,927 5.8 cpt
- **Township Fund** $1,089,757 3.2 cpt
- **Taconite Municipal Aid**** $5,952,563 17.8 cpt
- **Taconite Railroad** $591,142 1.8 cpt
- **Mining Effects**** $1,634,030 4.9 cpt
- **Special City/ Township Fund** $157,055 0.4 cpt
  - **Transferred from schools for cities/townships pay 2018 levy reduction** $255,023 0.7 cpt

School Districts
$21,807,784
65.1 cpt

- **Taconite School $0.0343 Fund**** $1,423,998 4.2 cpt***
- **Regular School $0.2472 Fund**** $9,173,173 27.4 cpt***
- **Taconite Railroad** $1,106,935 3.3 cpt ***
- **Building Maintenance Fund** $1,296,839 3.9 cpt
- **Taconite Referendum**** $6,178,596 18.4 cpt
- **School Bond Payments** $2,513,481 7.5 cpt
- **Taconite Levy Shortfall Payment** $369,785 1.1 cpt

Counties
$12,131,699
36.2 cpt

- **Regular County Fund**** $7,364,487 22.0 cpt
- **County Road and Bridge Fund**** $3,982,835 11.9 cpt
- **Taconite Railroad** $784,377 2.3 cpt

***($255,023) was subtracted from the Taconite School, Regular School and Tac RR funds for the Mountain Iron-Buhl district and used to reduce the pay 2018 levy of cities/townships within the district (0.7 cpt).

Property Tax Relief and Misc.
$11,296,703
33.7 cpt

- **Taconite Property Tax Relief** $11,296,703 33.7 cpt

Iron Range Resources & Rehabilitation (IRRR)
$38,769,693
115.6 cpt

- **IRRR Fund**** $3,241,899 9.7 cpt
- **IRRR Fixed Fund** $1,252,520 3.7 cpt
- **Iron Range Higher Education Acct.** $1,676,219 5.0 cpt
- **Producer Grant & Loan Fund** $2,937,302 8.7 cpt
- **Educational Revenue Bonds** $3,992,134 11.9 cpt
- **Iron Range School Cons. & Cooperatively Operated School Account** $5,860,104 17.5 cpt
- **Taconite Env. Protection Fund** $13,619,534 40.6 cpt
- **Douglas J. Johnson Economic Protection Trust Fund** $6,189,981 18.5 cpt

Guarantee Fund M.S. 298.225 M.S. 298.293

Other
$890,351
2.7 cpt

- **Taconite Economic Development Fund** $700,000 2.1 cpt
- **Range Association of Municipalities & Schools**** $123,303 0.4 cpt
- **Hockey Hall of Fame** $67,048 0.2 cpt

* Includes $7,375,366 from the State General Fund (22.0 cpt).

** Payments to the funds are guaranteed at a percentage level of the base year (1983 or 1999) by M.S. 298.225 for local aids and M.S. 298.293 for Property Tax Relief.

cpt = cents per taxable ton (cpt totals may not add up due to rounding).

Table of Contents

Data Charts

All figures are available in Excel format on our website. Go to www.revenue.state.mn.us and type **Mining Statistics** or **Ad Valorem** in the Search Box.

Subscribe for email updates

To be notified when new mining data is posted on the website, go www.revenue.state.mn.us and type **Mining** in the Search box. Click on “Mineral Taxes” then click on “Subscribe to Mining Taxes updates and information.”

The *Minnesota Mining Tax Guide* is printed on a limited basis by the Minnesota Department of Revenue. It is available on our website at **www.revenue.state.mn.us** or by calling 218-744-7424. Alternative formats for persons with visual impairments or other disabilities are provided upon request.

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Overview

The *Minnesota Mining Tax Guide* is published to identify all Minnesota mining-related taxes paid by the mining industry.

Production Tax

The Production Tax is the largest tax paid by the ferrous mining industry. It is a major source of revenue to the counties, municipalities and school districts within the Taconite Assistance Area. The Production Tax distributed in 2017 is the tax due for the 2016 production year. The tax rate for concentrates and pellets produced in 2016 was $2.659 per taxable ton. An additional tax of three cents per ton is imposed for each 1 percent that the iron content exceeds 72 percent. The taxable tonnage for 2016 is the average tonnage produced in 2014, 2015 and 2016. If this tax is imposed on other iron-bearing material, it is applied to the current-year production.

The inside front cover illustrates how the Production Tax is distributed. It shows both the cents per ton (cpt) distribution and the total amount distributed to various funds. The funds to which the Production Tax are distributed are explained on pages 4–9.

Occupation Taxes

Minnesota's Occupation Tax applies to mining and producing both ferrous minerals, such as taconite and iron ore, and nonferrous minerals, such as silver and copper. To date, only mining of ferrous minerals has occurred in Minnesota. More information relating to the Occupation Tax attributable to iron ore and taconite mining is available on pages 23–26.

State Taxes Incidental to Mining

Other state taxes impacted by mining include Sales and Use Tax and withholding on royalties. Go to revenue.state.mn.us and type **Mining** in the Search box. Follow the links to Sales Tax Fact Sheet 147 (Taconite and Iron Mining) or Withholding on Mining and Exploration Royalties.

Aggregate Material Tax

This tax is administered at the county level. For more information, go to www.revenue.state.mn.us and type **Aggregate** in the Search box.

County Taxes

Other Taconite and Iron Ore Ad Valorem (Property) taxes are paid directly to the counties. These are Property taxes assessed on auxiliary mining lands, unmined taconite, unmined natural iron ore, taconite railroads and severed mineral interests. These taxes are explained on pages 28-33.

Taxes on Nonferrous Minerals

While not subject to the Production Tax, nonferrous mining operations are subject to Occupation Tax, Net Proceeds Tax, and Ad Valorem Tax. These taxes are explained on page 34.

Figure 1

Iron Ore Production Comparison

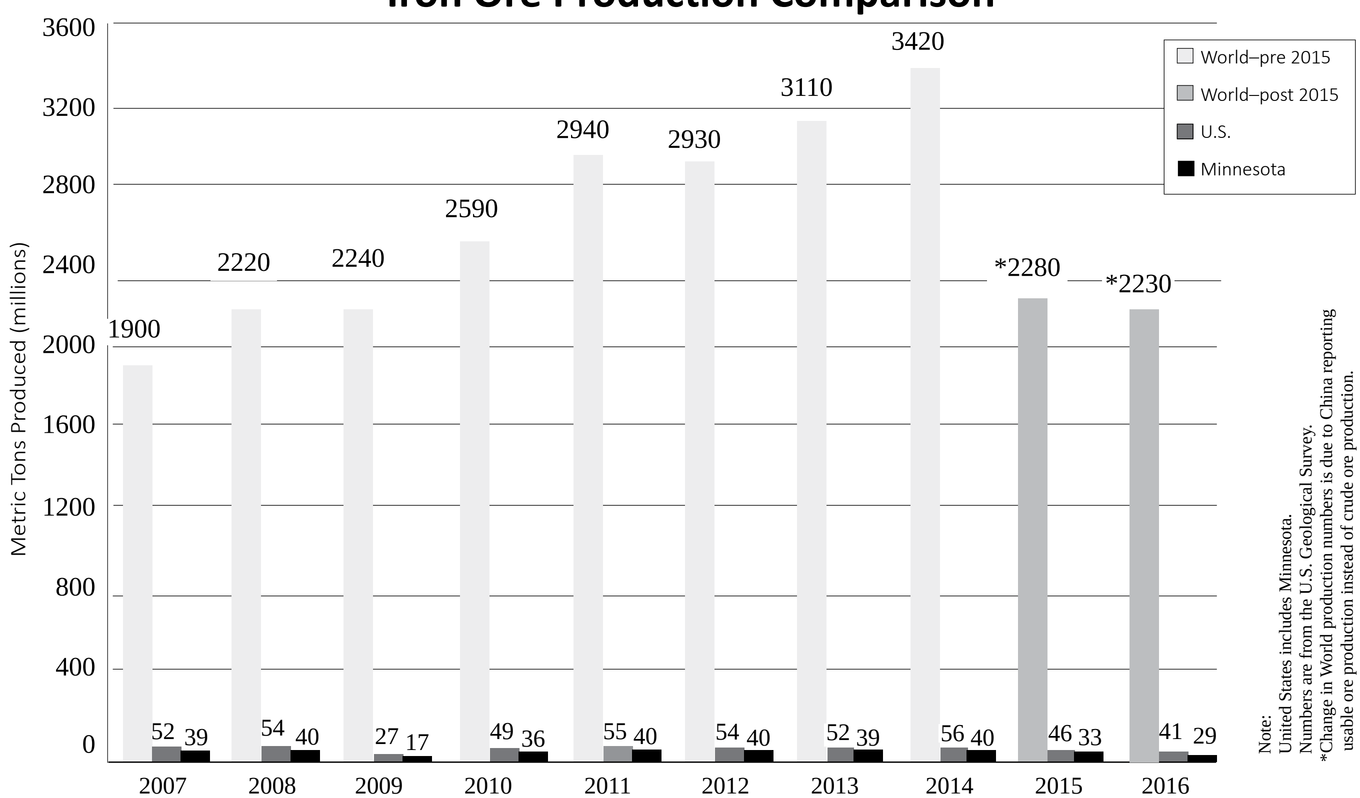


Figure 2
Minnesota Taconite Production Summary (2007–2016)

Year	ArcelorMittal	Hibbing Taconite	Northshore	U.S. Steel–Keewatin Taconite	U.S. Steel–Minntac	United Taconite	Total
2007	**2,495,201**	**7,265,682**	**4,975,108**	**5,220,394**	**12,750,828**	**5,278,708**	**37,985,921**
2008	**2,571,803**	**8,058,366**	**5,299,304**	**4,663,703**	**13,588,239**	**4,986,395**	**39,167,810**
2009	**1,364,783**	**1,693,512**	**3,081,289**	**74,680**	**7,087,356**	**3,777,486**	**17,079,106**
2010	**2,604,162**	**5,697,457**	**4,599,796**	**4,883,724**	**12,226,427**	**5,028,482**	**35,040,048**
2011	**2,625,659**	**7,604,595**	**5,591,721**	**4,969,039**	**13,047,915**	**5,095,221**	**38,934,150**
2012	**2,658,023**	**7,753,828**	**5,140,985**	**5,144,477**	**13,063,450**	**5,220,491**	**38,981,254**
2013	**2,645,243**	**7,312,252**	**3,776,603**	**4,956,740**	**13,448,911**	**5,081,692**	**37,221,441**
2014	**2,508,625**	**7,338,620**	**5,123,277**	**5,153,784**	**13,705,811**	**4,823,478**	**38,653,595**
2015	**2,490,099**	**7,760,305**	**4,168,373**	**1,702,877**	**11,491,695**	**3,011,800**	**30,625,149**
2016	**2,585,337**	**7,928,200**	**3,153,811**	**85,899**	**12,695,781**	**1,535,192**	**27,984,220**

Note:
- Historical data is available on our website.
- All weights are dry without flux.
- Production Tax report tonnages are used.

Figure 3
Minnesota Taxes Levied on Mining-Related Activity

Production Years	Unmined Taconite Tax	Use Tax (net)	Production Tax	Occupation Tax[1]	Railroad Gross Earnings Tax[2]	Total Taxes	Total Tons Produced[3]	Total Taxes per Ton
2007	495,033	6,603,598	85,644,627	10,358,000	12,275	103,113,533	37,985,921	2.71
2008	466,991	9,554,673	89,630,648	23,388,181	8,977	123,049,470	39,167,810	3.14
2009	238,274	(2,835,766)	74,255,473	340,000	9,612	72,007,593	17,079,106	4.22
2010	239,518	17,101,895	72,441,708	12,617,000	10,137	102,410,258	35,122,570*	2.92
2011	228,517	24,673,718	73,287,396	22,055,000	10,725	120,255,356	39,120,810*	3.07
2012	297,390	2,579,876	94,204,746	21,817,000	13,632	118,912,644	39,680,723	3.00
2013	279,594	24,636,760	101,214,301	15,776,560	34,082	141,941,297	38,481,228	3.69
2014	291,298	10,873,758	102,369,609	16,401,555	30,352	129,966,572	39,835,029	3.26
2015	299,722	(11,104,636)**	98,728,605	6,370,000	26,466	94,320,157	32,664,481	2.89
2016	**296,597**	**(13,958,786)****	**89,141,361**	**5,059,196**	**20,600**	**80,558,968**	**29,087,625**	**2.77**

Note:
Historical data is available on our website.
Taxes often levied (assessed) for one year and paid in the following year.
1 Amount paid (unaudited). Does not include adjustments.
2 Taconite railroads are taxed on an ad valorem basis.
3 Tons are dry without flux .
* Includes tonnage produced by Mesabi Nugget but not taxed under Production Tax.
** The Use Tax law changed mid 2015. Manufacturers no longer pay Use Tax on equipment used in the production process. As a result, more tax was refunded than collected.

Production Tax

(M.S. 298.24, 298.27 and 298.28)

Definition

The Production Tax is a severance tax paid on iron concentrates or pellets produced by the companies. It is paid in lieu of Ad Valorem (Property) taxes on taconite and lands containing taconite. Land and structures used in the production of the products are also excluded from Property Tax, with some exceptions. Electric power plants principally devoted to the generation of power for taconite mining and concentrating are considered to be used in the production of taconite (or direct reduced ore) and are covered by the *in lieu exemption* for Property taxes. If part of the power is used for other purposes, that proportion of the power plant is subject to the general Property Tax. The power plant must be owned by a company subject to Production Tax to qualify for the exemptions.

Tax Rate

The Production Tax rate for any given year is determined by multiplying the prior year's rate by the percentage change in the Gross Domestic Product Implicit Price Deflator (GDPIPD) from the fourth quarter of the second preceding year to the fourth quarter of the preceding year. The U.S. Department of Commerce publishes the GDPIPD monthly in *Survey of Current Business*. This escalator takes effect each year unless the rate is frozen or changed by the Minnesota State Legislature. The tax rate for the 2016 production year was $2.659 per taxable ton. For concentrates produced in 2017, the rate escalated to $2.701 per taxable ton.

Taxable Tons

The Production Tax is levied on taxable tons, which are the average tons produced during the current year and the previous two production years. This eliminates the peaks and valleys of tax payments by the taconite producers and distribution to the tax recipients. The result is a more stable tax base resembling a Property Tax. The tax for a producer of other iron bearing material is based on the current year production.

Distribution

Under Minnesota law, Production Tax revenues are distributed to various cities, townships, counties and school districts within the Taconite Assistance Area. This is an area comprising the present taconite mining areas plus areas where natural ore was formerly mined.

Funds are also allocated to the Minnesota Department of Iron Range Resources & Rehabilitation, which administers the Taconite Environmental Protection Fund (TEPF), the Douglas J. Johnson Economic Protection Trust Fund (DJJ) and the Taconite Economic Development Fund (TEDF) and other programs for the range cities, townships, schools, and the taconite industry. You can find more information at **mn.gov/irrrb**.

Payment Dates and Method

Fifty percent of the tax is due on or before February 24 and the remaining 50 percent is due on or before August 24. The Department of Revenue must notify each producer of its tax obligation for the year before February 15.

Each producer must make payments to six counties and Iron Range Resources & Rehabilitation on or before the due date. Payments are made to Aitkin, Cook, Crow Wing, Itasca, Lake and St. Louis Counties, and to Iron Range Resources & Rehabilitation. The county auditors then make payments to cities, townships, school districts, and other recipients.

Taconite Economic Development Fund (M.S. 298.227)

The Taconite Economic Development Fund (TEDF) was first created for production year 1992 at a rate of 10.4 cents per taxable ton.

No distribution is made under the TEDF in any year in which total industry production falls below 30 million tons. Any portion of the TEDF fund not released within one year of deposit is divided, with two-thirds to the Taconite Environmental Protection Fund and one-third to the Douglas J. Johnson Economic Protection Trust Fund. The 2001 legislature made the TEDF permanent at 30.1 cpt for distributions in 2002 and thereafter. The first 15.4 cents (of the 30.1 cents) did not require a matching investment by the company. A matching expenditure of at least 50 percent is required to qualify for the additional 14.7 cents per ton (above 15.4 cents). Beginning with distributions in 2014, a matching investment of the entire 30.1 cents is required. The legislature reduced the distributions to 25.1 cents beginning with 2015 distributions.

Each producer has two potential sources of TEDF money:

1. **Taxable production** — The Production Tax amount credited to each producer's share of the TEDF is 25.1 cpt.
2. **Chips, fines and concentrate** —An additional amount equal to 50 percent of the tax for chips, fines or concentrate sold not exceeding 5/16-inch, is allocated to each company's share of the TEDF. The total amount may not exceed $700,000 for all companies. If the total claimed exceeds $700,000, each company's share will be prorated. The determination of this allocation is based on current production year **sales** of chips, fines and concentrate—not the three-year average of production. Sales of crushed pellets *do not* qualify for this credit. [M.S. 298.28, subd. 9a(b).]

Therefore, each company is eligible to receive 25.1 cents per taxable ton plus an additional amount based on current year tons of chips and fines sold.

Fluxed Pellets

Fluxed pellets have limestone or other basic flux additives combined with the iron concentrates before pelletizing. Two facilities, ArcelorMittal and Minntac, produce fluxed pellets, although all have experimented with them. United Taconite, Hibbing Taconite, Keewatin Taconite and Northshore are producing a partially fluxed pellet containing a low percentage of limestone additives.

A flux credit is allowed against Production Tax. M.S. 298.24, subd. 1 (f) allows the weight of flux added to be subtracted from the pellet weight for Production Tax purposes. The taxable weight is the dry weight, less the weight of the flux. The weight of the flux is determined by a metallurgical calculation based on the analyses of the finished pellet, the concentrate and the flux stone. All tables in the *Minnesota Mining Tax Guide* with production statistics use an equivalent or calculated weight for fluxed pellets.

Occupation Tax is based on iron units and uses the full weight including flux.

Pellet Weighing

Pellet and concentrate tonnages are reported on a dry weight basis after the flux credit has been applied.

Definition of Taconite Tax Relief Area

One common prerequisite exists for all taconite aids and grants; the recipient must be within the geographic confines of the Taconite Tax Relief Area or the Taconite Assistance Area. This is defined by state laws (M.S. 273.134 and M.S. 273.1341) as follows:

"Taconite Tax Relief Area" means the geographic area contained within the boundaries of a school district that meets the following qualifications:

(1) It is a school district in which the assessed valuation of unmined iron ore on May 1, 1941, was not less than 40 percent of the assessed valuation of all real property and whose boundaries are within 20 miles of a taconite mine or plant; or

(2) It is a school district in which, on Jan. 1, 1977, or the applicable assessment date, there is a taconite concentrating plant or where taconite is mined or quarried or where there is located an electric generating plant which qualifies as a taconite facility.

Definition of Taconite Assistance Area

A "Taconite Assistance Area" means the geographic area that falls within the boundaries of a school district that contains a municipality in which the assessed valuation of unmined iron ore on May 1, 1941, was not less than 40 percent of the assessed valuation of all real property, or contains a municipality in which there was a taconite facility or taconite power plant on January 1, 1977. Any area within the Taconite Tax Relief Area is also considered to be within the Taconite Assistance Area.

State Appropriation (M.S. 298.285)

The Department of Revenue determines a state aid amount equal to a tax of 22 cents per taxable ton of iron ore concentrates. It is distributed under M.S. 298.28 as if the aid were Production Tax revenues. The aid is appropriated from the state's General Fund.

2017 Legislation

The 2017 legislature did not change any provisions of the Production Tax. However, the 2014 legislature made changes to the Production Tax distributions for the upcoming production years:

For the 2016 production year and forward: Beginning the production year after a taconite school bond receives its last taconite payment, an amount equal to what the bond received from the 2012 (pay 2013) production year distributions will be added to the Iron Range School Consolidation and Cooperatively Operated School Account with the amount being deducted from the same sources as the original bond.

For the 2023 production year and forward:

(1) The distribution to the Iron Range School Consolidation and Cooperatively Operated School Account will be reduced from 10 cents per ton to five cents per ton.

(2) The 10.525 cents per ton distribution to the County road and bridge fund will be increased to 15.525 cents per ton.

2017 Distribution of Funds (M.S. 298.28)

Subd. 2 – Cities and Towns Where Mining & Production is located

(a) The Taconite Cities and Towns Fund allocates 4.5 cents per ton to cities and towns where mining and concentrating occur. Fifty percent goes to cities and townships in which mining activity occurs. The remaining 50 percent goes to cities and townships in which concentrating occurs. *Note: This is done on a company-by-company basis.*

If both mining and concentrating take place in a single taxing district, the entire 4.5 cents is allocated there. If mining occurs in more than one city or town, the revenue (2.25 cpt) is divided based on either a percentage of taconite reserves or a four-year production average. Most taconite mines have mining in two or more areas.

If concentrating is split between two or more cities or towns, the revenue (2.25 cpt) is divided by the percentage of hours worked in each. The primary crusher is considered the first stage of concentration. Distribution detail is shown in *Figure 5*.

(b) Mining Effects — Four cents per taxable ton is allocated to cities and organized townships affected by mining because their boundaries are within three miles of a taconite mine pit that was actively mined in at least one of the prior three years. If a city or town is located near more than one mine meeting the criteria, it is eligible to receive aid calculated from only the mine producing the largest taxable tonnage. When more than one municipality qualifies for aid based on one company's production, the aid must be apportioned among the municipalities in proportion to their populations. The money must be used for infrastructure improvement projects.

(c) If there are excess distributions from the 3.43 cent, 24.72 cent, and taconite railroad school funds after covering the levy reduction in M.S. 126C.48, subd. 8, then the excess money must be distributed to the cities and townships within the school district in the proportion that their taxable net tax capacity within the school district bears to the net tax capacity of the school district for Property taxes payable in the year prior to distribution.

Subd. 3 – Taconite Municipal Aid Account

(a) The Taconite Municipal Aid is funded at 12.5 cents per taxable ton. The Kinney-White allocation (par. b and c) and the 0.3 cent Range Association of Municipalities and Schools (RAMS) allocation in subd. 8 are subtracted from it. The payment is made on September 15. Each city or township first receives the amount it was entitled to receive in 1975 from the Occupation Tax. The amount is then reduced according to the percentage aid guarantee provisions in M.S. 298.225. For example, if production levels mandate a 90 percent aid guarantee, then the Occupation Tax grandfather amount is also reduced to 90 percent. The remainder of the aid is distributed according to a complex formula using levies, valuation, population and fiscal need factors.

The first step in this formula is to determine the fiscal need factor (FNF). The FNF is a three-year average of the sum of the local government aid (LGA), local levy and Production Tax revenues received by the community. Next, the local effort tax capacity rate equals the fiscal need factor per capita (FNFPC) divided by 17. If the FNFPC is greater than 350, the local effort tax capacity rate (LETCR) is 350 divided by 17 plus the excess over 350 divided by 15. The minimum allowable LETCR is 8.16. The final step in this formula is to compute the distribution index (DI). The DI for a community equals its FNF minus LETCR times the adjusted net tax capacity divided by 100.

$$\text{If FNFPC} \le 350, \text{ LETCR} = \frac{\text{FNFPC}}{17}$$

$$\text{If FNFPC} > 350, \text{ LETCR*} = \frac{350}{17} + \frac{(\text{FNFPC}-350)}{15}$$

$$\text{DI} = (\text{FNF minus LETCR*}) \times \frac{\text{Adjusted Net Tax capacity}}{100}$$

* Minimum allowable LETCR = 8.16

A DI is determined for all eligible communities. A percentage is determined by comparing the DI of a particular community to the total of distribution indexes for all eligible communities. This percentage is then multiplied by the amount of available municipal aid to determine an amount for each community. Prior to this calculation, the Occupation Tax grandfather amounts and special aid for the city of Kinney and township of White are subtracted from the total available to the Taconite Municipal Aid Fund.

The conditions necessary for a municipality to qualify for this aid are identical to the qualifications for the 66 percent Taconite Property Tax Relief listed under subd. 6 (see page 7). The state laws governing Taconite Municipal Aid are M.S. 273.134, 298.28, subd. 1, Clause 2, and 298.282. Distribution detail is shown in *Figure 5*.

(b) and (c) - Additional money is allocated to cities and townships if more than 75 percent of the city's assessed valuation consisted of iron ore as of Jan. 2, 1980, or if more than 75 percent of the township's assessed valuation consisted of iron ore on Jan. 2, 1982. The distribution is calculated using certified levies, net tax capacities and population. Currently, only White Township and the city of Kinney qualify.

(d) The Township Fund was funded at 3 cents per ton for townships located entirely within the Taconite Tax Relief Area for 2009 distributions. For distributions in 2010 and subsequent years, the 3 cents is escalated in the same proportion as the Implicit Price Deflator as provided in M.S. 298.24, subd. 1. However, the escalation was frozen for distributions made in 2015 through 2017. The money is distributed to the townships on a per capita basis with a maximum of $50,000 per township. If a township would receive more than $50,000, the portion that exceeds $50,000 is redistributed among the townships under $50,000.

Subd. 4 – School Districts

(a) A total of 32.15 cents per taxable ton is allocated under (b) and (c), plus the amount in paragraph (d).

(b) (i) Taconite School Fund (3.43 cents)
A total of 3.43 cents per taxable ton for each producer is allocated to school districts in which mining and concentrating occurs. If the mining and concentrating take place in separate districts, 50 percent is allocated to the location of mining and 50 percent to concentrating. In addition, if the mining occurs in more than one school district, the 50 percent portion is further split based on either a four-year average of production or a percentage of taconite reserves. If the concentrating function of a company takes place in more than one school district, the 50 percent portion is further split according to hours worked in each district. The primary crusher, tailings basin and power plant owned by a taconite company are considered part of concentrating. When these are in different school districts from the plant, the hours-worked split is used. Distribution detail is shown in *Figure 6*.

(b) (ii) School Building Maintenance Fund (4 cents)

Four cents per taxable ton is allocated to specified school districts, based on proximity to a taconite facility, to be used for building maintenance and repairs. The money allocated from each taconite facility shall be apportioned between its recipient school districts based on pupil units.

a. Keewatin Taconite proceeds are allocated to the Coleraine and Nashwauk-Keewatin districts.
b. Hibbing Taconite proceeds are allocated to the Chisholm and Hibbing districts.
c. ArcelorMittal and Minntac proceeds are allocated to the Mountain Iron-Buhl, Virginia, Mesabi East and Eveleth-Gilbert districts.
d. Northshore Mining proceeds are allocated to the St. Louis County and Lake Superior districts.
e. United Taconite proceeds are allocated to the St. Louis County and Eveleth-Gilbert districts.

This additional money is not subject to the 95 percent levy limitations in M.S. 126C.48, subd. 8.

(c) Regular School Fund (24.72 cents)

A total of 24.72 cents per taxable ton is split among the 15 school districts in the Taconite Assistance Area. Each school district receives the amount it was entitled to receive in 1975 from the taconite Occupation Tax (under M.S. 298.32). This amount may be increased or reduced by the percentage aid guarantee provisions of M.S. 298.225. The remaining amount in the fund is distributed using an index based on pupil units and tax capacities. Generally, districts with larger tax capacities per pupil unit tend to receive a proportionately smaller amount of this fund. Eleven cents per ton of this distribution is not subject to the 95% levy limitation in M.S. 126C.48, subd. 8. Distribution detail is shown in *Figure 6*.

The index is calculated as follows: The pupil units for the prior school year are multiplied by the ratio of the average net tax capacity per pupil unit of all taconite districts to the adjusted net tax capacity per pupil unit of the district. Each district receives the portion of the distribution that its index bears to the sum of the indexes for all taconite school districts.

(d) Taconite Referendum Fund (21.3 cents)

The Taconite Referendum Fund (TRF) receives an allocation of 21.3 cents per taxable ton. Taconite school districts receive money from the fund on July 15 based on two calculations: (1) an additional $175 per pupil unit over and above state aids by passing a special levy referendum equal to 1.8 percent of net tax capacity. The pupil units used in the computation are the greater of the previous year or the 1983-84 school year units. The fund pays the difference between the local levy and $175 per pupil unit. (2) A second calculation equal to 22.5 percent of the amount obtained by subtracting 1.8 percent of the district's net tax capacity from the district's 2012 weighted average daily membership times the sum of (A) $415, plus (B) the district's fiscal year 2013 referendum allowance. If any money remains in the fund, it is distributed to the Taconite Environmental Protection Fund (two-thirds) and the Douglas J. Johnson Economic Protection Trust Fund (one-third). *Note: A district receiving money from the TRF must reserve the lesser of $25 or the amount received per pupil unit (of the $175 authorized) for early childhood programs or outcome-based learning programs. Distribution detail is shown in Figure 6.*

(e) Each school district is entitled to receive the amount it received in 1975 under M.S. 298.32 (Occupation Tax Grandfather).

Subd. 5 – Counties

(a) The allocation of 21.05 cents per taxable ton to counties (subject to adjustment by M.S. 298.225) is to be distributed under subd. 5(b) through (d). The amounts listed in (b) and (d) are the statutory amounts prior to any adjustment by M.S. 298.225. Distribution detail is shown in *Figure 8*.

(b) Taconite Counties with Mining or Concentrating

An amount of 10.525 cents per taxable ton is distributed to the county in which the taconite is mined or quarried or in which the concentrate is produced (split in the same manner as taconite cities and towns), less any amount distributed in subd. 5(c). Distribution detail is shown in *Figure 8*.

(c) Counties - Electric Power Plant

If an electric power plant owned by and providing the primary source of power for a taconite plant is located in a county other than the county in which the mining and concentrating processes are conducted, one cent per ton (for that company) is distributed to the county in which the power plant is located. *This one cent is not escalated but is subject to M.S. 298.225 adjustment with variable guarantee*.

Cook County continues to receive aid based on Minnesota Power's power plant, located in Taconite Harbor, due to the guarantee provided by M.S. 298.225. (Minnesota Power has owned and operated the power plant since purchasing it during LTV's bankruptcy in 2001.) For the 2016 production year, this amounted to $81,335. The one cent per ton distribution for the 1983 base year was figured on 9,793,639 tons. The current year M.S. 298.225 guarantee percentage is always applied.

$0.01 x 9,793,639 x 83.048786% = $81,335

There is also a transfer of $18,709 ({1983 base of $22,528} x 83.048786%) to the county fund covered in subd. 6(b). Therefore, Cook County receives a total of $100,044 due to the power plant.

(d) Taconite County Road and Bridge
Each county receives a portion of the aid that is deposited in the County Road and Bridge Fund in the same manner as taconite cities and towns. The basic allocation is 10.525 cents per taxable ton and will increase to 15.525 cents per taxable ton beginning with the 2024 distributions. It is subject to adjustment as in M.S. 298.225. Distribution detail is shown in *Figure 8*.

Subd. 6 – Taconite Property Tax Relief

(a) Taconite Property Tax Relief
The amount sent to this fund was rebased by the 2013 legislature at 34.8 cents per taxable ton for the 2013 production year. The fund will resume indexing by using the Gross Domestic Product Implicit Price Deflator beginning with the 2017 production year. The qualifications and distribution of Taconite Property Tax Relief are described in the following paragraphs.

The *Taconite Homestead Credit* reduces the tax paid by owners of certain properties located on the Mesabi and Vermillion ranges located within the Taconite Tax Relief Area. The properties receiving this credit are owner-occupied homes and owner-occupied farms.

If an owner-occupied home or farm is located in a city or town that contained at least 40 percent of its valuation as iron ore on May 1, 1941, or which had a taconite mine, processing plant, or electric generating facility on January 1, 1977, or currently has a taconite mine, processing plant, or electric generating facility, the taconite credit is 66 percent of the tax, up to a maximum credit of $315.10 for taxes payable in 2016.

If the property is not located in such a city or town, but is located in a school district containing such a city or town, the taconite credit is 57 percent of the tax, up to a maximum credit of $289.80.

The total amount of Taconite Property Tax Relief paid in each county and school district and an example of the calculation are available on our website.

State laws governing Taconite Property Tax Relief are contained in M.S. 273.134 to M.S. 273.136 and M.S. 298.28, subd. 6. This is guaranteed by the Douglas J. Johnson Economic Protection Trust Fund as stated in M.S. 298.293.

(b) Electric Power Plant Aid from Property Tax Relief
For any electric power plant located in another county, as described in 5(c), 0.1875 cent per taxable ton (cpt) from the Taconite Property Tax Relief Account is paid to the county. The distribution is subject to the M.S. 298.225 variable guarantee. For the 2016 production year, $18,709 was distributed, with the entire amount coming from the M.S. 298.225 guarantee (calculation details under (c) Counties).

(c) Electric Power Plant Aid from Property Tax Relief
This subdivision allocates 0.4541 cent per LTV's taxable tonnage to the Cook County school district due to LTV's power plant in Cook County. The distribution is subject to the M.S. 298.225 guarantee at 31.2 percent or the variable rate, whichever is less. For the 2016 production year, $21,087 was distributed. This is calculated by multiplying the 1983 base of $67,586 x .312 = $21,087.

Subd. 7 – Iron Range Resources & Rehabilitation

An amount of 6.5 cents per taxable ton escalated by the Gross National Product Implicit Price Deflator is allocated to Iron Range Resources & Rehabilitation (subject to M.S. 298.225 guarantee). However, the escalation is frozen for distributions made in 2015 through 2017. The funds are used by Iron Range Resources & Rehabilitation for general operating expenses and community development grants.

Subd. 7a – Iron Range School and Consolidation and Cooperatively Operated School Account

This account was created by the 2014 legislature and is managed by Iron Range Resources & Rehabilitation. It will receive distributions from the following:

(a) For distribution years 2015 through 2023 it will receive 10 cents per taxable ton. Beginning with distribution year 2024, it will be reduced to 5 cents per ton.

(b) For distribution years 2015, 2016 and 2017, the fund received two-thirds of the amount generated by any increase of the tax rate due to change in the implicit price deflator. For distribution year 2015, the calculated amount was the two-thirds of the dollar amount generated due to the tax rate change. For 2016, it was the calculated amount for 2015, plus the amount calculated for 2016. For 2017, it was the amounts calculated for 2015 and 2016, plus the amount calculated for 2017.

(c) Also, beginning the distribution year after a taconite school bond receives its last taconite payment, an amount equal to what the bond received from the 2012 pay 2013 production year distributions will be added to the fund with the money being deducted from the same sources as the original bond. The first bond eligible was Ely with distributions beginning in 2017.

Subd. 8 – Range Association of Municipalities & Schools (RAMS)

An amount equal to 0.3 cent per taxable ton (subject to M.S. 298.225 guarantee) is paid to the RAMS to provide an area-wide approach to problems that demand coordinated and cooperative actions. All cities, towns and schools in the taconite and iron ore mining area are included. This amount is subtracted from the Taconite Municipal Aid distribution in subd. 3.

Subd. 9 – Douglas J. Johnson Economic Protection Trust Fund (DJJ)

In addition to the amount provided in the remainder after all other distributions are completed, 3.35 cents per taxable ton is allocated to the DJJ. The cents per ton is normally increased in the same proportion as the implicit price deflator as provided in M.S. 294.24, subd 1. However, the escalation for this fund was frozen for distributions in 2015 through 2017.

In addition to the above, for distributions in 2015 through 2017, the DJJ received one-third of the tax generated due to the increase in the tax rate.

Subd. 9a – Taconite Economic Development Fund

This subdivision is explained on page 3.

Subd. 9b – Producer Grants

Five cents per taxable ton must be paid to the Taconite Environmental Protection Fund (TEPF) for use under M.S. 298.2961, subd. 4. The fund also receives a fixed amount equal to the increased tax proceeds due to the tax rate change for 2005 distributions, as stated in subd. 10 (b).

Subd. 9c – City of Eveleth

The City of Eveleth shall receive 0.20 cents per taxable ton for support of the Hockey Hall of Fame provided that an equal amount of donations have been received. Any amount of the 0.20 cents per ton that exceeds the donations shall be distributed to Iron Range Resources & Rehabilitation.

Subd. 9d – Iron Range Higher Education Account

Five cents per taxable ton must be allocated to Iron Range Resources & Rehabilitation to be deposited in the Iron Range Higher Education Account to be used for higher education programs conducted at educational institutions in the Taconite Assistance Area defined in M.S. 273.1341. The Iron Range Higher Education committee under M.S. 298.2214 and Iron Range Resources & Rehabilitation must approve all expenditures from the account.

Subd. 10 – Indexing

Beginning with distribution in 2000 (1999 production year), the amounts determined under subd. 6, paragraph (a), and subd. 9 are increased in the same proportion as the increase in the implicit price deflator as provided in M.S. 298.24, subd. 1.

Subd. 11 – Remainder

(a) After calculating the initial distributions to the various funds and grandfathered amounts including (b) & (c) below, the remainder is distributed two-thirds to the TEPF and one-third to the DJJ. Any interest earned on money on deposit by the counties is sent to Iron Range Resources & Rehabilitation to be split into the two funds using the same two-thirds/one-third apportionment.

(b) Taconite Railroad
Until 1978, the taconite railroad gross earnings tax was distributed to local units of government based on a formula of 50 percent to school districts, 22 percent city or town, 22 percent county, and six percent state. The respective shares were further split based on miles of track in each government unit. Beginning in 1978, the distributions were frozen at the 1977 level and funded from Production Tax revenues. The total amount distributed in 2017 was $2,482,454. Taconite railroad aids are not subject to the percentage reduction mandated for other aids by M.S. 298.225 and so remain constant from year to year. Beginning with the 2002 production year, the taconite railroad distribution to schools was reduced to 62 percent of the 1977 amount.

(c) Occupation Tax Grandfather Amount to Iron Range Resources & Rehabilitation
In 1978 and each year thereafter, the amount distributed to Iron Range Resources & Rehabilitation was the same as it received in 1977 from the distribution of the taconite and iron ore Occupation taxes: $1,252,520.

Additional Payments

In Minnesota Laws 2013, Chapter 143, Article 11, Section 11, the legislature authorized the commissioner of Iron Range Resources & Rehabilitation to issue $38,000,000 in revenue bonds to make grants to school districts within the Taconite Assistance Area. The grants are to be used for various building projects with the exception of ISD 2142 which must use the grant for debt service reduction for a bond passed in 2009. The revenue bonds are paid from Production Tax revenues prior to the calculation of the remainder under M.S. 298.28, subd. 11, with a maximum of 10 cents per ton. Any amount above 10 cents per ton will be paid by the DJJ fund.

Although the following payments are not included in M.S. 298.28 or its subdivisions, they are subtracted after dividing the remainder described in subd. 11.

These payments consist of school bond payments to school districts within the Taconite Tax Relief Area and Taconite Assistance Area. Most are funded 80 percent taconite and 20 percent local efforts.

In Minnesota Laws 2005, Chapter 152, Article 1, Section 39 the legislature authorized the commissioner of Iron Range Resources & Rehabilitation to issue $15,000,000 in revenue bonds to make grants to school districts in the Taconite Tax Relief Area or Taconite Assistance Area. The bonds are to be used by the school districts to pay for health, safety and maintenance improvements. The bonds are funded in equal shares from the TEPF and the DJJ. Minor amendments were made by the 2006 legislature.

Aid Guarantee (M.S. 298.225)

The recipients of the Production Tax, provided in M.S. 298.28, subds. 2 to 5, subd. 6, paragraphs (b) and (c) and subds. 7 and 8, are guaranteed to receive distributions equal to the amount distributed to them with respect to the 1983 production year, provided that production is not less than 42 million taxable tons. If the production is less, the amount distributed from the fund is reduced proportionately by two percent per each 1,000,000 tons by which the taxable tons are less than 42 million tons. For example, if the taxable tonnage (three-year average) is 39.8 million then the proportionate reduction is 4.4 percent. This is calculated by multiplying two percent times 2.2 million tons.

This aid guarantee is funded equally from the initial current year distributions to the TEPF and the DJJ. If the initial distributions are insufficient to fund the difference, the commissioner of Iron Range Resources & Rehabilitation makes the payments of any remaining difference from the existing balance of the TEPF and the DJJ in equal proportions.

The commissioner of the Minnesota Department of Revenue determines the amounts. The aid payments covered by this variable guarantee are listed as follows:

1. 4.5 cents—Taconite Cities and Towns Fund (uses 1999 production year as base year)
2. 12.2 cents—Taconite Municipal Aid Account
3. 21.3 cents— Taconite Referendum Fund
4. 6.5 cents—escalated to Iron Range Resources & Rehabilitation
5. 0.3 cent—RAMS
6. 0.1875 cent—Electric Power Plant Aid is transferred from Taconite Property Tax Relief Account to Cook County
7. 4 cents - Mining Effects Fund (uses 1999 production year as base year)

The following funds are guaranteed at 75 percent or the variable guarantee, whichever is less:

1. 10.525 cents—Taconite County Fund
2. 10.525 cents—Taconite County Road and Bridge Fund

The following funds are guaranteed at 31.2 percent or the variable guarantee, whichever is less:

1. 24.72 cents—Regular School Fund
2. 3.43 cents—Taconite School Fund
3. 0.4541 cent—Electric Power Plant Aid is transferred from Taconite Property Tax Relief Account to School District 166, Cook County

The Taconite Property Tax Relief Account is not covered by M.S. 298.225, but is separately guaranteed by the DJJ, as stated in M.S. 298.293.

Production Tax Distribution Calculation (M.S. 298.28)

The producers make the Production Tax payments directly to six counties (Cook, Lake, St. Louis, Itasca, Crow Wing and Aitkin) and Iron Range Resources & Rehabilitation. Each county auditor is responsible for making the taconite aid payments to the various jurisdictions within the county. St. Louis County was designated as fiscal agent for the Taconite Property Tax Relief Account and issues Taconite Property Tax Relief checks to the other counties. The state of Minnesota also makes a payment of 22 cents per taxable ton (payable 2017). This money was added to the amount available for distribution.

The Minnesota Department of Revenue makes all computations regarding the amount paid by the companies, state and the aid payments due to cities, schools, townships, counties and Iron Range Resources & Rehabilitation. Interest earnings on undistributed funds are remitted by the counties to Iron Range Resources & Rehabilitation.

The proceeds of the 2016 Production Tax (payable 2017) were distributed as follows:

M.S. 298.28	Payment Recipients	Cents per Taxable Ton
Subd. 2a	Taconite cities and towns	4.5
Subd. 2b	Taconite cities and towns (mining effects)	4.0
Subd. 3	Taconite Municipal Aid Account	12.2
Subd. 3(d)	Township Fund	3.0*
Subd. 4	School districts	
	(b)(i) Taconite schools (mining and/or concentrating in the district)	3.43
	(b)(ii) School Building Maintenance Fund	4.0
	(c) Regular School Fund (distributed by formula)	24.72
	(d) Taconite Referendum Fund	(formula amount–see page 6)
Subd. 5	Counties	
	(b and c) Taconite counties (includes electric power plant)	10.525
	(d) Taconite county Road and Bridge	10.525
	Counties total	21.05
Subd. 6	Taconite Property Tax Relief (includes .6416 cents for Cook County and Cook County Schools)	34.8*
Subd. 7	Iron Range Resources & Rehabilitation	6.5*
Subd. 7a	Iron Range School Consolidation and Cooperatively Operated School Account	10.0
Subd. 8	Range Association of Municipalities and Schools	0.3
Subd. 9	Douglas J. Johnson Economic Protection Trust Fund	3.35*
Subd. 9a	Taconite Economic Development Fund	25.1
Subd. 9b	Taconite Environmental Fund for use in Producer Grants	5.0**
Subd. 9c	City of Eveleth (Hockey Hall of Fame)	0.2
Subd. 9d	Iron Range Higher Education Account	5.0
Subd. 10	Indexing provisions	-
Subd. 11	Distribution of remainder	-

* These funds are escalated using the Gross Domestic Product Implicit Price Deflator. After escalation, the cents per ton for Township fund was 3.25 cents, Taconite Property Tax Relief was 34.8 cents, Iron Range Resources & Rehabilitation was 8.75 cents, and the Douglas J. Johnson Economic Protection Trust Fund was 4.44 cents.

** Plus amount of revenue due to tax increase generated in pay 2005.

The full amount distributed, including escalation and M.S. 298.225 guarantees, is available in *Figure 4*.

Taconite Environmental Protection Fund (TEPF) and Douglas J. Johnson Economic Protection Trust Fund (DJJ) (M.S. 298.223 and 298.291)

The TEPF and the DJJ were established by the 1977 Legislature. These two funds receive the remainder of the Production Tax revenues after all distributions are made according to M.S. 298.28. The remainder is split with one-third to the DJJ and two-thirds going to the TEPF.

The TEPF was created for the purpose of reclaiming, restoring and enhancing those areas of Minnesota that are adversely affected by environmentally damaging operations involved in mining and producing taconite and iron ore concentrate. The scope of activities includes local economic development projects. The Minnesota Department of Iron Range Resources & Rehabilitation commissioner administers the fund.

The DJJ is somewhat different in that only interest and dividends earned by the fund may be spent before January 1, 2028. Expenditures from the principal may be made with approval from Iron Range Resources & Rehabilitation for economic development projects.

Note: The DJJ and TEPF Fund Balances table is available on our website as an Excel file. Go to www.revenue.state.mn.us and type **Mining Statistics** in the Search box.

Taconite Property Tax Relief

The taconite homestead credits described on page 7 are administered by the county auditors. The amounts do not equal the total Production Tax allocated for Property Tax Relief shown in the tables as collections or payments. The difference is carried in the Taconite Property Tax Relief Fund balance with St. Louis County as fiscal agent. If the fund balance and Production Tax collections are not sufficient to make the payments, the deficit is made up from the Douglas J. Johnson Economic Protection Trust Fund. The last time this occurred was in 1989.

Note: The Taconite Property Tax Relief Fund Balance, Taconite Property Tax Relief Fund Distribution, and Taconite Residential Homestead Credit Examples tables are available on our website as Excel files. Go to www.revenue.state.mn.us and type **Mining Statistics** in the Search box.

Figure 4

Distribution by Fund/Recipient*

Production Year	2012	2013	2014	2015	2016
City and Township (Mining/Concentrating)	$2,066,752	$2,134,737	$2,125,786	$2,062,198	$1,940,927
Cities and Towns (Mining Effects)	1,758,238	1,794,389	1,789,718	1,699,835	1,634,030
Taconite Municipal Aid Account	6,355,475	6,633,334	6,589,995	6,475,364	5,952,563
Taconite Municipal Aid — Special City/ Township Fund	157,055	157,055	157,055	157,055	157,055
Township Fund	1,223,128	1,287,505	1,281,952	1,220,270	1,089,757
County Fund	9,000,065	9,095,093	7,114,672	7,313,951	7,364,487
County Road and Bridge Fund	4,486,556	4,623,110	4,605,134	4,405,415	3,982,835
Regular School Fund	6,908,326	10,676,982	10,634,759	10,165,680	9,173,173
Taconite School Fund	1,566,247	1,610,748	1,604,891	1,539,803	1,423,998
School Building Maintenance Fund	1,506,072	1,535,158	1,531,417	1,420,003	1,296,839
Taconite Levy Shortfall Payment	–	–	–	–	369,785
Taconite Referendum Fund	3,091,236	6,178,596	6,178,596	6,178,596	6,178,596
School Bond Payments	3,363,147	2,631,867	2,608,285	2,606,617	2,513,481
Taconite Railroad Aid (total for cities, towns, counties, schools)	2,482,454	2,482,454	2,482,454	2,482,454	2,482,454
Taconite Property Tax Relief Fund	16,493,071	13,783,501	13,724,064	13,063,708	11,296,703
Iron Range Resources & Rehabilitation (IRRR) (Indexed)	3,636,468	3,819,425	3,803,209	3,623,063	3,241,899
IRRR (Fixed)	1,252,520	1,252,520	1,252,520	1,252,520	1,252,520
Taconite Economic Development Fund (TEDF)	12,231,412	12,621,936	10,598,678	10,122,388	700,000
Taconite Environmental Protection Fund (TEPT)	13,318,892	12,938,216	12,993,550	11,392,335	13,619,534
TEPF Producer Grants and Loans	3,176,600	3,241,471	3,232,931	3,138,053	2,937,302
Douglas J. Johnson Economic Protection Trust Fund (DJJ)	5,017,442	5,080,122	5,633,213	5,036,933	6,189,981
Iron Range Higher Education Account	1,915,517	1,980,388	1,971,848	1,876,970	1,676,219
IRRR Educational Revenue Bonds	1,411,925	4,147,804	3,993,464	3,990,434	3,992,134
Iron Range School Consolidation...Acct–	–	–	4,916,476	5,552,584	5,860,104
Hockey Hall of Fame	76,621	79,216	78,874	75,079	67,048
Range Association of Municipalities and Schools (RAMS)	137,802	142,382	142,200	135,963	123,303
Excess School Levy Replacement Money**	(1,742,074)	(2,313,588)	(633,976)	(97,157)	0
Levy Replacement Money to Cities/Townships**	1,742,074	2,313,588	633,976	97,157	0
Unallocated School Levy Replacement Money***	–	–	–	–	(255,023)
School Money to Cities and Towns for Pay 2018 Levy Reduction***	–	–	–	–	255,023
Total	**$102,633,021**	**$109,928,009**	**$111,045,741**	**$106,987,271**	**$96,516,727**

Dash indicates not eligible.

* The Production Tax is collected and distributed in the year following production. For example, the 2016 Production Tax was collected and distributed during 2017.

** If the combined total of the School District Fund, Regular School Fund and Taconite Railroad exceeds the levy replacement amount, the excess is transferred to cities and townships within the district.

*** If a school district does not allocate all of its eligible levy replacement amount, the unallocated amount is used to reduce the following year's levy for cities and towns within the district.

Figure 5

2017 Distribution by Fund to Cities and Townships

(Based on 2016 production year tax revenues)

	Mining & Concentrating 4.5 cents	Mining Effects 4.0 cents	M.S. 298.28, subd. 3(b)	Township Fund 3.0 cents	Taconite Railroad Aid	Taconite Municipal Aid	Transferred from Schools*	Total
Aitkin County								
Aitkin	–	–	–	–	–	–	$0	$0
Aitkin Township	–	–	–	–	–	–	$0	$0
Farm Island Township	–	–	–	–	–	–	$0	$0
Fleming Township	–	–	–	–	–	–	$0	$0
Glen Township	–	–	–	–	–	–	$0	$0
Hazelton Township	–	–	–	–	–	–	$0	$0
Kimberly Township	–	–	–	–	–	–	$0	$0
Lakeside Township	–	–	–	–	–	–	$0	$0
Lee Township	–	–	–	–	–	–	$0	$0
Libby Township	–	–	–	–	–	–	$0	$0
Logan Township	–	–	–	–	–	–	$0	$0
Malmo Township	–	–	–	–	–	–	$0	$0
Morrison Township	–	–	–	–	–	–	$0	$0
Nordland Township	–	–	–	–	–	–	$0	$0
Palisade	–	–	–	–	–	–	$0	$0
Spencer Township	–	–	–	–	–	–	$0	$0
Verdon Township	–	–	–	–	–	–	$0	$0
Waukenabo Township	–	–	–	–	–	–	$0	$0
Wealthwood Township	–	–	–	–	–	–	$0	$0
Workman Township	–	–	–	–	–	–	$0	$0
Cook County								
Grand Marais	–	–	–	–	–	–	$0	$0
Lutsen Township	–	–	–	$15,961	–	–	$0	$15,961
Schroeder Township	$7,377	–	–	$7,922	$47,700	$0	$0	$62,999
Tofte Township	–	–	–	$9,607	–	–	$0	$9,607
Crow Wing County								
Bay Lake Township	–	–	–	–	–	–	$0	$0
Center Township	–	–	–	–	–	–	$0	$0
Crosby	–	–	–	–	–	$195,755	$0	$195,755
Crosslake	–	–	–	–	–	–	$0	$0
Cuyuna	–	–	–	–	–	–	$0	$0
Deerwood	–	–	–	–	–	–	$0	$0
Deerwood Township	–	–	–	–	–	–	$0	$0
Emily	–	–	–	–	–	–	$0	$0
Fairfield Township	–	–	–	–	–	–	$0	$0
Irondale Township	–	–	–	–	–	$26,219	$0	$26,219
Ironton	–	–	–	–	–	$46,791	$0	$46,791
Lake Edward Township	–	–	–	–	–	–	$0	$0
Little Pine Township	–	–	–	–	–	–	$0	$0
Mission Township	–	–	–	–	–	–	$0	$0
Nokay Township	–	–	–	–	–	–	$0	$0
Oak Lawn Township	–	–	–	–	–	–	$0	$0
Pelican Township	–	–	–	–	–	–	$0	$0

*Transferred from schools for city/town levy reduction.

Figure 5 *(cont.)*

2017 Distribution by Fund to Cities and Townships

	Mining & Concentrating 4.5 cents	Mining Effects 4.0 cents	M.S. 298.28, subd. 3(b)	Township Fund 3.0 cents	Taconite Railroad Aid	Taconite Municipal Aid	Transferred from Schools*	Total
Perry Township	–	–	–	–	–	–	$0	$0
Rabbitt Lake Township	–	–	–	–	–	$0	$0	$0
Riverton	–	–	–	–	–	$2,923	$0	$2,923
Ross Lake Township	–	–	–	–	–	–	$0	$0
Trommald	–	–	–	–	–	$2,858	$0	$2,858
Wolford Township	–	–	–	–	–	$172	$0	$172
Itasca County								
Alvwood Township	–	–	–	–	–	–	$0	$0
Arbo Township	$33,136	–	–	–	–	–	$0	$33,136
Ardenhurst Township	–	–	–	–	–	–	$0	$0
Balsam Township	–	–	–	–	–	–	$0	$0
Bearville Township	–	–	–	–	–	–	$0	$0
Big Fork	–	–	–	–	–	–	$0	$0
Big Fork Township	–	–	–	–	–	–	$0	$0
Blackberry Township	–	–	–	–	–	–	$0	$0
Bovey	$0	–	–	–	–	$67,589	$0	$67,589
Calumet	–	–	–	–	–	$31,752	$0	$31,752
Carpenter Township	–	–	–	–	–	–	$0	$0
Cohasset	–	–	–	–	–	$0	$0	$0
Coleraine	$14,097	–	–	–	–	$82,874	$0	$96,971
Effie	–	–	–	–	–	–	$0	$0
Feeley Township	–	–	–	–	–	–	$0	$0
Good Hope Township	–	–	–	–	–	–	$0	$0
Goodland Township	–	–	–	$17,644	–	–	$0	$17,644
Grand Rapids	–	–	–	–	–	–	$0	$0
Grattan Township	–	–	–	–	–	–	$0	$0
Greenway Township	$16,885	–	–	$32,763	–	$28,384	$0	$78,032
Harris Township	–	–	–	–	–	–	$0	$0
Keewatin	$21,083	$58,693	–	–	–	$100,771	$0	$180,547
Kinghurst Township	–	–	–	–	–	–	$0	$0
LaPrairie	–	–	–	–	–	–	$0	$0
Lawrence Township	–	–	–	$17,185	–	–	$0	$17,185
Lone Pine Township	$5,010	$21,887	–	$15,272	–	$2,342	$0	$44,511
Marble	–	–	–	---	–	$48,909	$0	$48,909
Max Township	–	–	–	---	–	–	$0	$0
Moose Township	–	–	–	---	–	–	$0	$0
Nashwauk	$19,855	$54,140	–	---	–	$79,461	$0	$153,456
Nashwauk Township	$84,585	$37,959	–	$26,486	–	$14,442	$0	$163,472
Nore Township	–	–	–	---	–	–	$0	$0
Pomroy Township	–	–	–	---	–	–	$0	$0
Sago Township	–	–	–	---	–	–	$0	$0
Spang Township	–	–	–	---	–	–	$0	$0
Splithand Township	–	–	–	---	–	–	$0	$0

*Transferred from schools for city/town levy reduction.

Figure 5 *(cont.)*

2017 Distribution by Fund to Cities and Townships

	Mining & Concentrating 4.5 cents	Mining Effects 4.0 cents	M.S. 298.28, subd. 3(b)	Township Fund 3.0 cents	Taconite Railroad Aid	Taconite Municipal Aid	Transferred from Schools*	Total
Squaw Lake	–	–	–	–	–	–	$0	$0
Stokes Township	–	–	–	–	–	–	$0	$0
Taconite	$2,047	–	–	–	–	$21,337	$0	$23,384
Third River Township	---	–	–	–	–	–	$0	$0
Trout Lake Township	$373	–	–	–	–	–	$0	$373
Wabana Township	–	–	–	–	–	–	$0	$0
Warba	–	–	–	–	–	–	$0	$0
Wawina Township	–	–	–	–	–	–	$0	$0
Wildwood Township	–	–	–	–	–	–	$0	$0
Lake County								
Beaver Bay	–	–	–	–	–	–	$0	$0
Beaver Bay Township	$1,829	–	–	$18,257	$12,565	$0	$0	$32,651
Crystal Bay Township	–	–	–	$17,491	$6,951	–	$0	$24,442
Fall Lake Township	–	–	–	$19,826	–	–	$0	$19,826
Silver Bay	$88,163	–	–	–	$152,706	$223,527	$0	$464,396
Silver Creek Township	–	–	–	$41,566	$20,612	–	$0	$62.178
Stony River Township	–	–	–	$6,200	$19,943	–	$0	$26,143
Two Harbors	–	–	–	–	–	–	$0	$0
St. Louis County								
Alango Township	–	–	–	$9,607	–	–	$0	$9,607
Alborn Township	–	–	–	$17,606	–	–	$0	$17,606
Alden Township	–	–	–	$7,961	–	–	$0	$7,961
Angora Township	–	–	–	$9,071	–	–	$0	$9,071
Arrowhead Township	–	–	–	–	–	–	$0	$0
Ault Township	–	–	–	$4,325	–	–	$0	$4,325
Aurora	$14,499	$69,829	–	–	–	$162,687	$0	$247,015
Babbitt	$96,690	$161,078	–	–	$166,767	$196,245	$0	$620,780
Balkan Township	–	$11,704	–	$32,342	–	$15,761	$0	$59,807
Bassett Township	–	$4,861	–	$1,722	$11,745	–	$0	$18,328
Beatty Township	–	–	–	$13,435	–	–	$0	$13,435
Biwabik	$16,416	$27,274	–	–	–	$56,758	$0	$100,448
Biwabik Township	$25,549	$21,733	–	$30,773	–	$13,965	$0	$92,020
Breitung Township	–	–	–	$22,505	–	$0	$0	$22,505
Brevator Township	–	–	–	–	–	–	$0	$0
Brookston	–	–	–	–	–	–	$0	$0
Buhl	–	$36,946	–	–	–	$74,216	$27,203	$138,365
Camp 5 Township	–	–	–	$1,110	–	–	$0	$1,110
Cedar Valley Township	–	–	–	–	–	–	$0	$0
Cherry Township	–	–	–	$31,921	–	–	$0	$31,921
Chisholm	–	$69,336	–	–	–	$495,375	$0	$564,711
Clinton Township	–	$24,117	–	$38,619	–	–	$606	$62,736
Colvin Township	–	–	–	$11,521	–	–	$0	$11,521
Cook	–	–	–	–	–	–	$0	$0
Cotton Township	–	–	–	$17,377	–	–	$0	$17,377

*Transferred from schools for city/town levy reduction.

Figure 5 *(cont.)*

2017 Distribution by Fund to Cities and Townships

	Mining & Concentrating 4.5 cents	Mining Effects 4.0 cents	M.S. 298.28, subd. 3(b)	Township Fund 3.0 cents	Taconite Railroad Aid	Taconite Municipal Aid	Transferred from Schools*	Total
Crane Lake Township	–	–	–	$2,832	–	–	$0	$2,832
Culver Township	–	–	–	$11,177	–	–	$0	$11,177
Duluth Township	–	–	–	$50,000	–	–	$0	$50,000
Eagle’s Nest Township	–	–	–	$8,612	–	$0	$0	$8,612
Ellsburg Township	–	–	–	$8,191	–	–	$0	$8,191
Elmer Township	–	–	–	$5,703	–	–	$0	$5,703
Ely	–	–	–	–	–	$320,853	$0	$320,853
Embarrass Township	–	–	–	$23,118	–	–	$0	$23,118
Eveleth	$52,970	$87,721	–	–	–	$417,617	$0	$558,308
Fairbanks Township	–	–	–	$2,564	–	–	$0	$2,564
Fayal Township	$2,895	$42,880	–	$50,000	–	$25,188	$0	$120,963
Field Township	–	–	–	$14,965	–	–	$0	$14,965
French Township	–	–	–	$20,744	–	–	$0	$20,744
Gilbert	$14,916	$48,708	–	–	–	$172,995	$0	$236,619
Great Scott Township	$19,610	$14,236	–	$14,659	–	$12,830	$39,439	$100,774
Greenwood Township	–	–	–	$34,868	–	–	$0	$34,868
Hibbing	$445,243	$225,988	–	–	–	$1,404,086	$0	$2,075,317
Hoyt Lakes	$208,257	$83,472	–	–	$152,153	$225,766	$0	$669,648
Industrial Township	–	–	–	$30,276	–	–	$0	$30,276
Iron Junction	–	–	–	–	–	–	$0	$0
Kabetogama Township	–	–	–	$4,708	–	–	$0	$4,708
Kelsey Township	–	–	–	$5,167	–	–	$0	$5,167
Kinney	$11,936	$6,170	$33,525	–	–	$27,650	$5,969	$85,250
Kugler Township	–	–	–	$6,890	–	–	$0	$6,890
Lavell Township	–	–	–	$11,788	–	–	$0	$11,788
Leiding Township	–	–	–	$14,736	–	–	$0	$14,736
Leonidas	$4,999	$1,195	–	–	–	$5,090	$0	$11,284
Linden Grove Township	–	–	–	$5,129	–	–	$0	$5,129
McDavitt Township	$78,844	–	–	$16,880	–	$13,639	$0	$109,363
McKinley	–	$3,406	–	–	–	$11,067	$0	$14,473
Meadowlands	–	–	–	–	–	–	$0	$0
Meadowlands Township	–	–	–	$11,559	–	–	$0	$11,559
Morcom Township	–	–	–	$3,406	–	–	$0	$3,406
Morse Township	–	–	–	$46,274	–	–	$0	$46,274
Mountain Iron	$537,730	$107,717	–	–	–	$320,106	$176,325	$1,141,878
Ness Township	–	–	–	$2,373	–	–	$0	$2,373
New Independence TS	–	–	–	$11,138	–	–	$0	$11,138
Northland Township	–	–	–	$6,545	–	–	$0	$6,545
Orr	–	–	–	–	–	–	$0	$0
Owens Township	–	–	–	$9,645	–	–	$0	$9,645
Pequaywan Township	–	–	–	$4,632	–	–	$0	$4,632
Pike Township	–	–	–	$15,272	–	–	$0	$15,272
Portage Township	–	–	–	$6,200	–	–	$0	$6,200
Sandy Township	–	–	–	$13,090	–	–	$0	$13,090

*Transferred from schools for city/town levy reduction.

Figure 5 *(cont.)*

2017 Distribution by Fund to Cities and Townships

	Mining & Concentrating 4.5 cents	Mining Effects 4.0 cents	M.S. 298.28, subd. 3(b)	Township Fund 3.0 cents	Taconite Railroad Aid	Taconite Municipal Aid	Transferred from Schools*	Total
Stoney Brook Township	–	–	–	$12,783	–	–	$0	$12,783
Sturgeon Township	–	–	–	$5,014	–	–	$0	$5,014
Toivola Township	–	–	–	$6,622	–	–	$0	$6,622
Tower	–	–	–	–	–	$34,672	$0	$34,672
Vermillion Lake TS	–	–	–	$10,717	–	–	$0	$10,717
Virginia	$34,817	$319,323	–	–	–	$873,720	$6,087	$1,233,947
Waasa Township	---	$9,881	–	$9,148	–	–	$0	$19,029
White Township	$24,236	$62,924	$123,530	$50,000	–	$86,907	$0	$347,597
Willow Valley Township	–	–	–	$4,784	–	–	$0	$4,784
Winton	–	–	–	–	–	–	$0	$0
Wuori Township	$56,880	$20,852	–	$21,473	–	$9,264	$0	$108,469
Total	**$1,940,927**	**$1,634,030**	**$157,055**	**$1,089,757**	**$591,142**	**$5,952,563**	**$255,023**	**$11,620,497**

Dash indicates not eligible. $0 indicates eligible, but no payment at current valuation and production.
*Transferred from schools for city/town levy reduction.

Figure 6

2017 Distributions by Fund to School Districts

(Based on 2016 production year tax revenues)

School Districts	Taconite School Fund $0.0343	Regular School Fund $0.2472	Taconite Railroad Aid	School Bldg. Maintenance Fund $0.04	Taconite Referendum $0.213	Unallocated Levy Replacement Money Used for City/ Town Levy Reduction*	School Levy Replacements/ Shortfall Payment**	Total by School District
001 Aitkin	---	$265,388	---	---	$62,694	$0	$8,223	$336,305
166 Cook County	$21,087	$42,989	$264,977	---	$91,498	$0	$0	$420,551
182 Crosby-Ironton	---	$300,807	---	---	$222,602	$0	$3,153	$526,562
316 Greenway	$45,963	$923,235	---	$64,955	$372,009	$0	$7,827	$1,413,989
318 Grand Rapids	$25,257	$1,066,639	---	---	$428,400	$0	$0	$1,520,296
319 Nashwauk-Keewatin	$83,346	$332,059	---	$27,612	$268,675	$0	$43,445	$755,137
381 Lake Superior	$68,979	$438,100	$342,720	$72,670	$244,417	$0	$0	$1,166,886
695 Chisholm	---	$849,738	---	$79,427	$469,527	$0	$68,590	$1,467,282
696 Ely	---	$92,368	---	---	$213,624	$0	$0	$305,992
701 Hibbing	$294,822	$1,708,396	---	$227,601	$1,219,547	$0	$7,252	$3,457,618
706 Virginia	$70,628	$887,155	---	$198,996	$728,472	$0	$106,168	$1,991,419
712 Mtn. Iron-Buhl	$427,776	$435,647	---	$90,246	$349,776	($255,023)	$28,317	$1,076,739
2142 St. Louis County	$122,271	$531,845	$284,841	$176,847	$429,452	$0	$29,739	$1,574,995
2154 Eveleth-Gilbert	$80,532	$723,394	---	$207,356	$652,570	$0	$67,071	$1,730,923
2711 Mesabi East	$183,337	$575,413	$214,397	$151,129	$425,333	$0	$0	$1,549,609
Total	**$1,423,998**	**$9,173,173**	**$1,106,935**	**$1,296,839**	**$6,178,596**	**($255,023)**	**$369,785**	**$19,294,303**

Dashes indicate not eligible. $0 indicates eligible, but no payment at current valuation and production.

* Unallocated levy replacement money is used to reduce cities and township levies within the district the following year.
**Allocation is made from the Taconite Property Tax Relief Account to the school districts.

Figure 7
School Bond Payments

School Districts	Year Authorized[1]	Final Payment Year[2]	Payment[3]	Outstanding Balance[4]
166 Cook County[5]	1996	2016	$467,775	$0
316 Greenway	2000	2019	139,960	408,000
381 Lake Superior	2000	2022	354,611	1,696,047
695 Chisholm	2000	2020	276,055	1,060,821
706 Virginia	1996	2016	176,230	0
712 Mtn. Iron-Buhl	1998	2017	288,460	284,000
2154 Eveleth-Gilbert	1996	2017	310,390	312,800
2711 Mesabi East[5]	2008	2016	500,000	0
Total			**$2,513,481**	**$3,761,668**

1 Legislative year in which taconite funding was enacted.
2 Production year from which final bond payment will be deducted.
3 Payments made from 2016 pay 2017 tax distribution.
4 Estimated portion of outstanding bond balance to be paid by taconite funds (not including interest).
5 All taconite bonds funded at 80 percent taconite, 20 percent local effort, unless otherwise noted: Cook County – 1996, 70 percent ; Mesabi East – 2008, $500,000.

Figure 8
2017 Distribution by Fund to Counties
(Based on 2016 production year tax revenues)

County	Regular County 10.525 cents	Road and Bridge 10.525 cents	Taconite Railroad	Total by County
Cook	$100,044	–	$187,190	$287,234
Itasca	796,016	328,463	–	1,124,479
Lake	524,443	210,481	243,034	977,958
St. Louis	5,943,984	3,443,891	354,153	9,742,028
Total	**$7,364,487**	**$3,982,835**	**$784,377**	**$12,131,699**

Dash indicates not eligible.

Figure 9

2016 Taxable Production and Tax by Mine

(Includes taconite, DRI/iron nuggets and iron-ore concentrate)

Producer	Production Tons	Taxable Tonnage*	Production Tax Rate	Tax Assessed
ArcelorMittal	2,585,337	2,528,020	$2.659	$6,722,005
Hibbing Taconite	7,928,200	7,675,708	2.659	20,409,708
Magnetation	1,103,405	1,103,405	2.659	2,933,954
Mesabi Nugget	0	0	2.659	0
Mining Resources	0	0	2.659	0
Northshore	3,153,811	4,148,487	2.659	11,030,827
U.S. Steel-Keewatin Taconite	85,899	2,314,187	2.659	6,153,423
U.S. Steel-Minntac	12,695,781	12,631,096	2.659	33,586,084
United Taconite	1,535,192	3,123,490	2.659	8,305,360
Total	**29,087,625**	**33,524,393**	**$2.659**	**$89,141,361**

* The taxable tonnage is the average production of the current year and previous two years.
Magnetation and Mining Resources pay on current-year production only.

Mesabi Nugget, Mining Resources and Keewatin Taconite were idled throughout 2016. The tonnage shown for Keewatin Taconite was for concentrate normally stored for pellet production but was sold and considered subject to the Production Tax.

Figure 10

2016 Production Tonnage by Product Type

Producer	Pellets			Chips and Fines			DRI	Total by Mine
	Acid	Fluxed	Partial Fluxed	Acid	Fluxed/ Partial Fluxed	Concentrate	Nuggets	
ArcelorMittal	**–**	**2,545,674**	**–**	**–**	**39,663**	**–**	**–**	**2,585,337**
Hibbing Taconite	**–**	**–**	**7,928,200**	**–**	**–**	**–**	**–**	**7,928,200**
Magnetation	**–**	**–**	**–**	**–**	**–**	**1,103,405**	**–**	**1,103,405**
Mesabi Nugget	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**0**
Mining Resources	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**0**
Northshore	**–**	**–**	**3,072,598**	**–**	**64,722**	**16,491**	**–**	**3,153,811**
U.S. Steel-Keewatin Taconite	**–**	**–**	**–**	**–**	**–**	**85,899**	**–**	**85,899**
U.S. Steel-Minntac	**1,242,052**	**11,407,436**	**–**	**–**	**46,293**	**–**	**–**	**12,695,781**
United Taconite	**–**	**–**	**1,508,459**	**–**	**26,733**	**–**	**–**	**1,535,192**
Total	**1,242,052**	**13,953,110**	**12,509,257**	**0**	**177,411**	**1,205,795**	**0**	**29,087,625**

Dash indicates not produced.

* Partially fluxed pellets contain less than 2 percent flux.
Keewatin Taconite's tonnage was for concentrate shipped from stockpile.

Figure 11

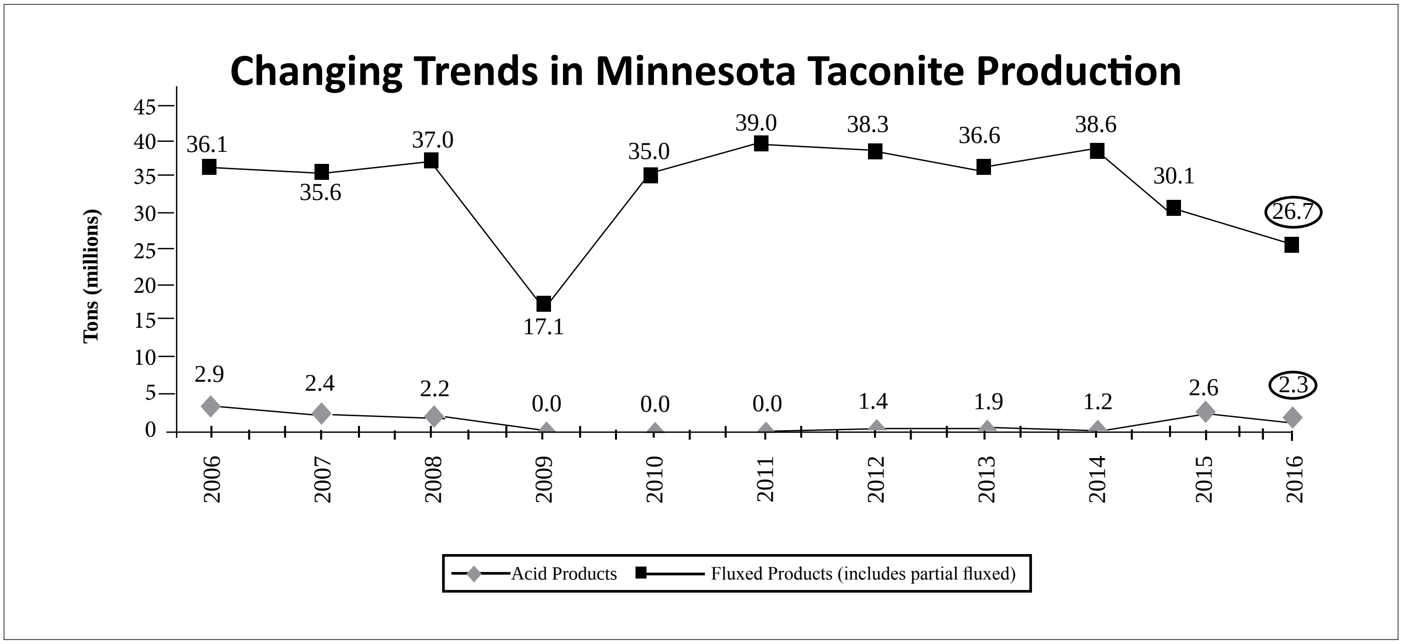

Changing Trends in Minnesota Taconite Production
Tons (millions)
45
40
35
30
25
20
15
10
5
0
36.1
35.6
37.0
17.1
35.0
39.0
38.3
36.6
38.6
30.1
26.7
2.9
2.4
2.2
0.0
0.0
0.0
1.4
1.9
1.2
2.6
2.3
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Acid Products
Fluxed Products (includes partial fluxed)

Figure 12

Production Tax Rate History and Index Summary

Production Year	Statutory	Fe (iron)	Inflation	Total	TEDF
2006	210.3 cents	0	10.0 (IPD) cents	220.3 cents	30.1 cents
2007	210.3 cents	0	15.5 (IPD) cents	225.8 cents	20.1 cents
2008	210.3 cents	0	21.3 (IPD) cents	231.6 cents	30.1 cents
2009	210.3 cents	0	26.1 (IPD) cents	236.4 cents	30.1 cents
2010	210.3 cents	0	27.7 (IPD) cents	238.0 cents	30.1 cents
2011	210.3 cents	0	30.9 (IPD) cents	241.2 cents	30.1 cents
2012	210.3 cents	0	36.2 (IPD) cents	246.5 cents	30.1 cents
2013	256.0 cents*	0	0.0 (IPD) cents	256.0 cents	30.1 cents
2014	256.0 cents	0	3.7 (IPD) cents	259.7 cents	25.1 cents
2015	256.0 cents	0	7.0 (IPD) cents	263.0 cents	25.1 cents
2016	256.0 cents	0	9.9 (IPD) cents	265.9 cents	25.1 cents
2017	**256.0 cents**	**0**	**14.1 (IPD) cents**	**270.1 cents**	**25.1 cents**

Historical data available on website.

*The 2013 legislature changed the statutory rate to $2.560 per ton for the 2013 production year, with indexing to resume with the 2014 production year.

Figure 13

Taconite Produced and Production Tax Collected

Year	Production Tons (000s)	Production Tax (000s)	Collected Rate Per Production Ton	Taxable Tons (000s)	Tax Rate Per Taxable Ton
2006	38,948	84,451	2.168	38,335	2.203
2007	37,986	85,645	2.255	37,929	2.258
2008	39,168	89,631	2.288	38,701	2.316
2009	17,079	74,255	4.348	31,411	2.364
2010	35,049	72,442	2.067	30,438	2.380
2011	38,968	73,287	1.881	30,384	2.412
2012	39,681	94,205	2.374	38,310	2.465
2013	38,481	101,214	2.630	39,608	2.560
2014	39,835	102,370	2.570	39,437	2.597
2015	32,664	98,729	3.023	37,539	2.630
2016	**29,088**	**89,146**	**3.065**	**33,524**	**2.659**

Historical data is available on our website.

A three-year average is used, except for other iron-bearing material which uses the current year.

Direct Reduced Iron (DRI)

Because it is subject to the Production Tax, a DRI production plant and facilities is exempt from regular ad valorem (Property) taxes. The taxable tonnage is based on a three-year production average. Pig iron is considered DRI for the purpose of Production Tax and incentives.

A steel plant would be subject to ad valorem (Property) taxes as would any other business. If a steel plant were in conjunction with a DRI plant, the DRI portion would be subject to the Production Tax, thus exempt from Ad Valorem (Property) taxes.

Reduced Production Tax Rate for DRI

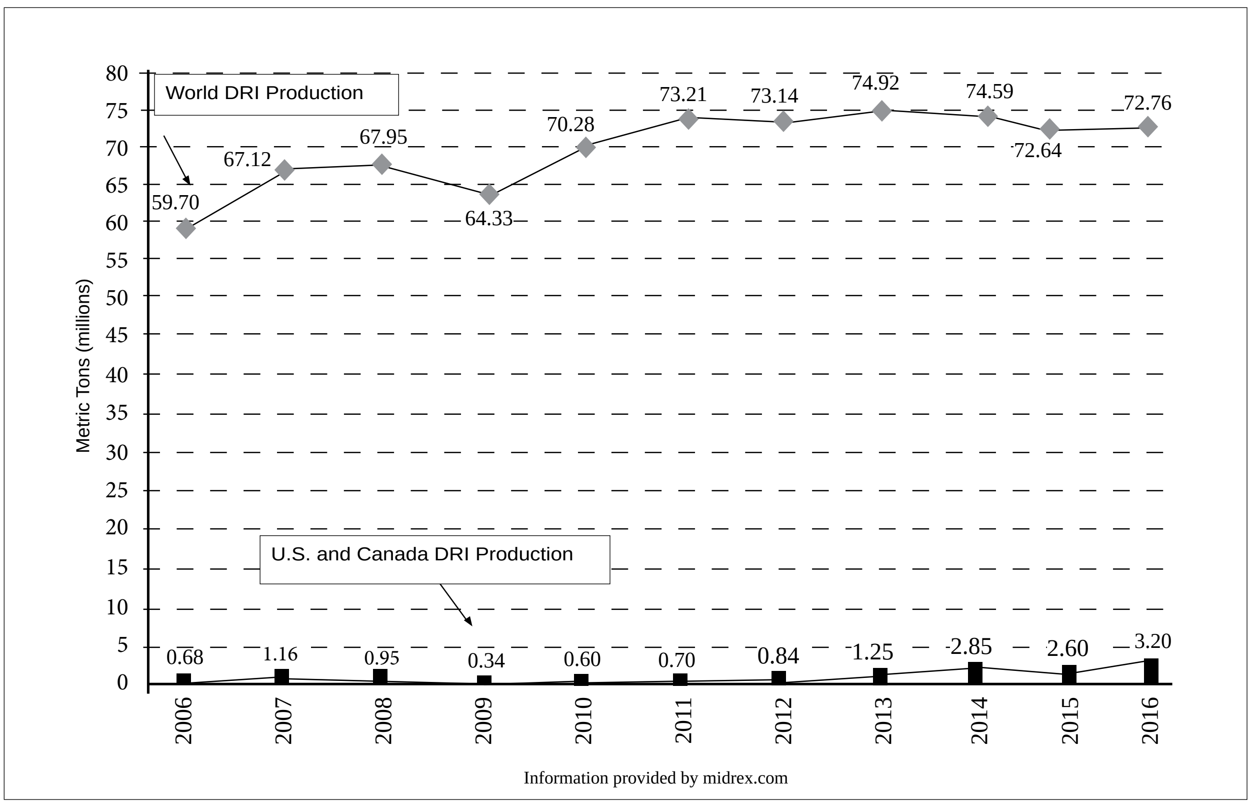
The first five years of a DRI plant's commercial production are subject to reduced tax rates if all environmental permits have been obtained and construction has begun before July 2, 2008. Commercial production is defined as more than 50,000 tons.

Years of operation	% of regular rate	Years of operation	% of regular rate
1	0%	4	50%
2	0%	5	75%
3	25%	6	100%

The Production Tax rate for DRI is the regular rate plus an additional three cents per gross ton for each one percent that the iron content exceeds 72 percent when dried at 212 degrees Fahrenheit. Thus, at a base Production Tax rate for 2017 of $2.701 per ton, the tax rate for 90 percent iron DRI would be $3.241. The rate for 95 percent DRI would be $3.391.

Figure 14

World Direct Reduced Iron Production



Occupation Tax

(M.S. 298.01, 298.16 – 298.18)

Minnesota's Occupation Tax applies to mining and producing both ferrous and nonferrous minerals, including taconite and iron ore, and other minerals such as gold, silver, copper, nickel and titanium.

The Occupation Tax is paid in lieu of the Corporate Franchise Tax on mining activities. Generally, it is determined in the same manner as Minnesota's Corporate Franchise Tax under M.S. 290.02 but there are a few exceptions:

- The unitary provisions of the Corporate Franchise Tax law do not apply to Occupation Tax.
- Mining companies may use percentage depletion.
- The alternative minimum tax (AMT) does not apply.
- All sales are Minnesota sales, so 100 percent of net income is assigned to Minnesota.
- The tax rate is 2.45 percent.

Ferrous Minerals

Gross income from mining or producing ferrous minerals is based on "mine value;" i.e., the value of the products produced *after* beneficiation or processing, but *prior* to any stockpiling, transportation, marketing and marine insurance, loading or unloading costs.

The procedure for determining a company's mine value was developed by the Minnesota Department of Revenue and representatives from the taconite industry in 1990. The department sets product values each year, which are generally based on the following:

1) Seventy-five percent of the change in the product value is based on the change in the Steel Mill Products Index (SMPI) from June of the previous year to June of the current year; and

2) Twenty-five percent of the change in product value is based on actual transaction prices of products sold in nonequity sales as reported by the mining companies.

When ferrous minerals, such as taconite pellets, chips or concentrate, are used by the producer or disposed of or sold in a **non-arms-length transaction**, the company must use the product values set by the department to determine the mine value for Occupation Tax.

Non-arms-length transactions include, but are not limited to, any sales or shipments to: 1) any steel producer having any ownership interest in the selling or shipping company, or 2) any steel producer affiliated or associated with any firm having any ownership or other financial interest in the selling or shipping company.

For **nonequity or arms-length transactions**, a company may choose to determine the mine value by using either 1) actual sales prices (f.o.b. mine) or 2) the product values set by the department. It must select one of these options the first time a nonequity sale is made. *Once it selects an option, however, it must continue to use that option for all nonequity sales in the future*. Requests to change the selected option must receive approval from the department.

Product Values

Acid Pellets: The value of acid pellets is based on the change in the SMPI from June of the previous year to June of the current year (75%), and actual sales prices of nonequity sales (25%).

Flux Pellets: The value of flux pellets is based on the acid pellet value, adjusted based on the amount of flux in the finished pellets.

- *Partial Flux (less than 2 percent flux)*: Pellets with 1.99 percent or less flux are valued at $0.015 per Fe (iron) unit higher than the acid pellet value.
- *Flux*: Pellets with 2 percent or more flux are valued at $0.015 per Fe (iron) unit higher than the acid pellet value *per each 1 percent of flux* in the finished pellet.

Chips, Fines and Concentrate: Acid chips (fines) and concentrate are valued at 75 percent of the acid pellet value. Flux chips and concentrate are valued at 75 percent of the flux pellet value.

2016 Product Values per Iron Unit

Value per Fe (iron) unit (per dry gross ton) for the period January 1 – December 31, 2016:

	Value
Acid pellets	$1.043 per iron unit
Pellet chips (fines) and concentrate	75% of acid or fluxed pellet price
Flux pellets – partial flux (.1% – 1.99% flux)	$1.043 + $0.015 = $1.058
Flux (2.00% and higher flux) *	$1.043 + $0.015 per iron unit for each 1% flux
Direct reduced iron (DRI)	$4.101 per iron unit

***Example:** Pellet with 4.8% flux in finished pellet: 4.0 × $0.015 = $0.060
Mine value: $1.043 + $0.060 = $1.103

Direct Reduced Iron (DRI): The value of DRI is based on the change in the SMPI from June of the previous year to June of the current year (100%). There are currently insufficient nonequity sales reported to determine a nonequity sales factor.

Acid Pellet and DRI Values 2012–2016		
	Acid Pellets (per iron unit)	**DRI** (per iron unit)
2012	1.368	5.043
2013	1.294	4.634
2014	1.336	4.829
2015	1.137	4.250
2016	1.043	4.101

Nonferrous Minerals

Gross income from mining or producing nonferrous minerals, such as copper, nickel, gold, etc., is calculated differently from the method used for ferrous minerals.

For **nonequity or arms-length transactions**, gross income is based on actual sales. Generally, for **non-arms-length transactions**, gross income is based on the average annual market price as published in the *Engineering and Mining Journal*.

Occupation Tax Distribution

All Occupation Tax revenue is deposited in the state's General Fund. Ten percent is used for the general support of the University of Minnesota and 40 percent for elementary and secondary schools. Fifty percent remains in the General Fund.

Of the amount remaining in the General Fund, the following appropriations are made based on taxable tonnage. For 2017 the taxable tonnage was 33,524,393 tons.

Region 3 Counties: An amount equal to 1.5 cents per taxable ton is appropriated to the Iron Range Resources & Rehabilitation for counties in Region 3 not qualifying for Taconite Property Tax Relief. Only Carlton and Koochiching counties qualify. These funds must be used to provide economic or environmental loans or grants.

Region 3 Distributions			
2012	$455,767	2015	$591,554
2013	$574,655	2016	$563,091
2014	$594,116	2017	$502,866

Department of Natural Resources. An amount equal to 2.5 cents per taxable ton is appropriated to the Mining Environmental and Regulatory Account managed by the Department of Natural Resources. These funds must be used for work on environmental issues and to provide regulatory services for ferrous and nonferrous mining operations in the state. The distribution is made by July 1 annually. The amount distributed in 2017 was $838,110.

Iron Range Resources & Rehabilitation. An amount equal to 6 cents per taxable ton is appropriated to the Iron Range School Consolidation and Cooperatively Operated School Account managed by Iron Range Resources & Rehabilitation The distribution is made on May 15 annually starting in 2015. The amount distributed in 2017 was $2,011,464.

Figure 15
Employment and Mine Value by Mine
Production Year 2016

Company	Employment	Tons Produced	Mine Value*
ArcelorMittal	355	2,739,889	$191,510,977
Hibbing Taconite	705	7,954,932	555,792,481
Northshore	508	3,204,954	218,753,408
U.S. Steel-Keewatin Taconite	38	86,260	4,622,247
U.S. Steel-Minntac	1,360	13,179,120	917,453,562
United Taconite	474	1,683,735	115,197,957
Total – Taconite	**3,440**	**28,848,890**	**$2,003,330,632**
Mesabi Nugget	0	0	0
Total – DRI	**0**	**0**	**0**
Magnetation	181	**	**
Mining Resources	0	0	0
Total – Natural Ore	**181**	**0**	**$0**
Total – All	**3,621**	**28,848,890**	**$2,003,330,632**

* The mine value is based on product values set by the Minnesota Department of Revenue. It does not represent actual sales by companies.
** Information not provided.

Figure 16

Occupation Tax by Company*

	2009 (000s)	2010 (000s)	2011 (000s)	2012 (000s)	2013 (000s)	2014 (000s)	2015 (000s)	2016 (000s)
ArcelorMittal	$0	$0	$50	$700	$250	$460	$0	$460
Hibbing Taconite	0	300	4,550	4,360	3,165	2,320	2,300	2,170
Northshore	340	707	2,015	1,545	360	1,350	490	600
U.S. Steel	0	9,600	13,400	12,187	9,320	10,622	3,150	1,829
United Taconite	0	2,010	2,040	3,000	2,000	1,650	430	0
Total – Taconite	**$340**	**$12,617**	**$22,055**	**$21,792**	**$15,095**	**$16,402**	**$6,370**	**$5,059**
Mesabi Nugget	$0	$0	$0	$0	$0	$0	$0	$0
Total – DRI	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Magnetation	$0	$0	$0	$25	$682	$0	$0	$0
Mining Resources	0	0	0	0	0	0	0	0
Total – Natural Ore	**$0**	**$0**	**$0**	**$25**	**$682**	**$0**	**$0**	**$0**
Total	**$340**	**$12,617**	**$22,055**	**$21,817**	**$15,777**	**$16,402**	**$6,370**	**$5,059**

* Amount paid by May 1 each year. Does not include adjustments.

Figure 17

Occupation Tax by Product Type*

(Iron Ore, Direct Reduced Ore, Taconite)

	Iron Ore		Direct Reduced Iron		Taconite		Total	
Year	Tons Produced (000s)	Occupation Tax (000s)	Tons Produced (000s)	Occupation Tax (000s)	Tons Produced (000s)	Occupation Tax (000s)	Tons Produced (000s)	Occupation Tax (000s)
2009	71	$0	-	$0	17,645	$340	17,716	$340
2010	90	0	74	0	35,984	12,617	36,148	12,617
2011	168	0	153	0	39,771	22,055	40,092	22,055
2012	704	25	175	0	39,873	21,792	40,752	21,817
2013	1,360	682	211	0	38,064	15,095	39,635	15,777
2014	1,323	0	238	0	39,487	16,402	41,048	16,402
2015	2,182	0	46	0	31,306	6,370	33,534	6,370
2016	**	**$0**	**0**	**$0**	**28,849**	**$5,059**	**28,849**	**$5,059**

Dash indicates not applicable. $0 indicates eligible, but no payment at current valuation and production.

* Amount paid by May 1 each year. Does not include adjustments.
** Information not provided.

Figure 18
Occupation Tax Averages – Taconite Only

Year	Tons Produced (000s)	Average Value	Cost of Beneficiation	Cost of Mining	Development	Production & Property Tax Paid	Sales and Use Tax Paid	Admin. and Misc. Expense	Royalty	Taxable Value of Production	Occupation Tax Paid
2012	39,873	90.18	30.78	13.31	1.59	2.63	0.21	3.91	3.90	33.83	0.55
2013	38,064	85.38	32.66	13.57	1.64	2.50	0.27	5.15	3.73	25.87	0.40
2014	39,487	88.33	34.49	13.62	1.56	2.39	0.23	5.72	3.58	26.73	0.42
2015	31,306	75.47	29.75	11.67	1.57	2.84	0.24	11.53	2.75	15.13	0.20
2016	**28,849**	**69.44**	**28.09**	**11.41**	**1.30**	**2.82**	**0.14**	**11.19**	**2.24**	**12.25**	**0.18**

Cost of Beneficiation

Year	Tons Produced (000s)	Beneficiation Labor (000s)	Per Ton	Beneficiation Supplies (000s)	Per Ton	Beneficiation Depr. and Int. (000s)	Per Ton	Beneficiation Misc. Per Ton	Total Beneficiation Per Ton
2012	39,873	174,099	4.37	912,601	22.89	61,823	1.55	1.97	30.78
2013	38,064	192,824	5.07	911,656	23.95	60,179	1.58	2.06	32.66
2014	39,487	204,916	5.19	1,010,582	25.59	68,438	1.73	1.98	34.49
2015	31,306	126,091	4.03	567,283	18.12	59,238	1.89	5.71	29.75
2016	**28,849**	**105,894**	**3.67**	**480,282**	**16.65**	**56,491**	**1.96**	**5.81**	**28.09**

Cost of Mining

Year	Tons Produced (000s)	Mining Labor (000s)	Per Ton	Mining Supplies (000s)	Per Ton	Cost of Mining	Mining Depreciation (per ton)	Total Mining Costs Per Ton
2012	39,873	133,369	3.34	352,359	8.84	12.18	1.13	13.31
2013	38,064	134,025	3.52	344,632	9.05	12.57	1.00	13.57
2014	39,487	143,213	3.63	353,534	8.95	12.57	1.04	13.62
2015	31,306	95,766	3.06	215,817	6.89	9.94	1.72	11.67
2016	**28,849**	**92,924**	**3.22**	**183,053**	**6.35**	**9.57**	**1.85**	**11.41**

This information is provided by Minnesota mining companies and is not audited by the Minnesota Department of Revenue.

Ad Valorem Tax on Auxiliary Mining Lands for Taconite Operations

(M.S. 272.01)

Lands and structures actively used for taconite production are exempt from the Ad Valorem Tax and are subject to the Production Tax *in lieu* of Property Tax. Actively used lands include the plant site, mining pit, stockpiles, tailings pond and water reservoirs. Also included are lands stripped and ready for mining, but not lands merely cleared of trees. It is important to note that this exemption applies only to the Ad Valorem Tax on the land and buildings and *not to the Unmined Taconite Tax* described on the following page. Lands adjacent to these facilities, commonly referred to as auxiliary mining lands, are subject to assessment of Ad Valorem Tax administered by the county.

The county assessor is responsible for estimating the market value of auxiliary mining lands and classifying them into one of several property classifications established by Minnesota law. The two most common property classifications used on auxiliary mining lands are industrial and rural vacant land. In general, lands in close proximity to active taconite operations are assigned the industrial classification while those further away are classified as rural vacant land. The classification of property is covered in M.S. 273.13.

Each property classification has a legislatively set percentage called the class rate that is multiplied by the property's taxable market value (TMV) to calculate tax capacity. For taxes payable 2016, the class rate for rural vacant land is 1.00 percent of the estimated market value. For the industrial classification, there are two class rates: 1.50 percent for the first $150,000 of the TMV and 2.0 percent for the value over $150,000.

Property taxes are calculated by multiplying a property's tax capacity times the tax extension rate for the jurisdiction where it is located. Tax extension rates are determined by county, local government and school district spending. In St. Louis County within the mining area for taxes payable in 2017, they range from a low of approximately 85 percent to a high of approximately 261 percent. In addition, the market value times the referendum rate must be added to the tax determined above if there is a referendum in the taxing district. For industrial class property, the state general tax rate of 45.802 percent applies in addition to the local tax rate.

The following schedule provides for adjustments in both the valuations and classifications of auxiliary mining lands located on the iron formation versus off-formation lands as well as further refinements based on the proximity of these lands to active mining operations. It outlines valuation adjustments to be made on excess lands where they are located as market conditions and/or Minnesota statutes dictate (see below). This schedule was updated based on market conditions for the 2016 assessment.

St. Louis County Mining Land Assessment Schedule

1. Iron formation land	**Value ($/acre)**	**Classification**
A. Land within ¼ mile of active pit	$1000	Industrial
B. Excess land (more than ¼ mile from mining activity or outside 15-year pit limit).		
1. Undisturbed	Same as other private land	Rural Vacant Land or current use
2. Disturbed		
a. Stockpiles	75% of other private land	Rural Vacant Land or current use
b. Abandoned Pits	50% of other private land	Rural Vacant Land or current use
2. Off-formation land		
A. Land within ¼ mile of mining activity	$700	Industrial
B. Excess Land		
1. Undisturbed	Same as other private land	Rural Vacant Land or current use
2. Tailings Ponds		
a. Stockpiles	75% of other private land	Rural Vacant Land or current use
b. Tailings Ponds	30% of other private land	Rural Vacant Land or current use

Ad Valorem Tax on Unmined Taconite

(M.S. 298.26)

A tax not exceeding $15 per acre may be assessed on the taconite or iron sulfides in any 40-acre tract from which the production of iron ore concentrate is less than 1,000 tons.

The heading in the statute is somewhat misleading since it refers to a *Tax on Unmined Iron Ore or Iron Sulfides*. The tax clearly applies to unmined taconite and has been administered in that manner. The term "iron ore" does not refer to high-grade natural ore in this instance.

The tax, as presently administered, applies to all iron formation lands on the Mesabi Range. The statutory exemption administered by the county assessor provides that in any year in which at least 1,000 tons of iron ore concentrates are produced from a 40-acre tract or government lot, the tract or lot are exempt from the Unmined Taconite Tax. The county assessors have also exempted actual platted townsites that are occupied.

The iron formation lands on the Mesabi Range are divided into two categories by the Minnesota Department of Revenue. This is done through the evaluation of exploration drill hole data submitted by the mining companies.

The categories are:

1) Lands that are underlain by magnetic taconite of sufficient quantity and grade to be currently economic: They are considered to be economic taconite and are given a market value of $500 per acre.

2) Lands either not believed or not known to be underlain by magnetic taconite of current economic quantity, quality and grade: They are considered to be uneconomic taconite and are given a market value of $25 per acre.

To be classified as economic taconite, category 1, the taconite must pass the following criteria:

— contain more than 16 percent magnetic iron with the Davis tube test;

— contain less than 10 percent concentrate silica (SiO_2) with the Davis tube test;

— have a 15- to 25-foot minimum mining thickness; and

— have a stripping ratio of less than four-to-one (waste/concentrate), calculated as follows:

A) Surface (ft.) x 1.5= Equiv. Ft. Surface

B) Rock (ft.) x 2.25 = Equiv. Ft. Waste

C) $\frac{\text{Ore (ft.) x 2.5}}{3}$ = Equiv. Ft. Concentrate

Stripping Ratio = $\frac{A + B}{C}$

If the material fails any of the above criteria, then it is considered to be *uneconomic* taconite and classified as category 2. Some lands may also be considered as uneconomic due to environmental restrictions.

For taxes payable in 2017, the tax is calculated by multiplying the market value for the parcel of land by the 2.00 percent class rate to obtain the tax capacity. The special rate on the first $150,000 of market value that applies to class 3 commercial/industrial property does not apply to class 5 unmined taconite. This is then multiplied by the local tax rate. *Note: Call your county auditor for more information.*

Figure 19

Ad Valorem Tax on Unmined Taconite

(Year payable)

County	2010	2011	2012	2013	2014	2015	2016	2017
Itasca	$ 0	$ 0	$ 0	$ 32,283	$ 32,468	$ 31,498	$ 43,838	$ 41,697
St. Louis	238,274	239,518	228,517	265,107	247,126	259,800	255,884	254,900
Total	**$238,274**	**$239,518**	**$228,517**	**$297,390**	**$279,594**	**$291,298**	**$299,722**	**$296,597**

Ad Valorem Tax on Unmined Natural Iron Ore

(M.S. 272.03, 273.02, 273.12, 273.13, 273.165, 273.1104)

Since 1909, Minnesota's natural iron ore reserves have been estimated and assessed by the state for Ad Valorem Tax purposes. The actual Ad Valorem Tax levy is set by the county, the school district and the local township or municipality. The county auditor collects the tax levy.

A Minnesota Supreme Court decision in 1936 established the present worth of future profits method for valuing the iron ore reserves. This is accomplished through the use of a complex formula known as the Hoskold Formula. The formula takes into account ore prices and all the various cost factors in determining the value of the unmined ore.

Each year, the Minnesota Department of Revenue uses a five-year average for allowable costs taken from the Occupation Tax report. A five-year average of the Lake Erie iron ore market value is also used. These averages are used to help reduce fluctuation of value due to sudden cost/price changes.

The following expenses are allowed as deductions from the Lake Erie market value on the computation of present worth, which is known as the Hoskold Formula:

- 1a. Mining, normal costs
- 1b. Mining, special costs
- 2. Beneficiation
- 3. Miscellaneous (Property Tax, medical ins., etc.)
- 4. Development (future)
- 5. Plant and equipment (future)
- 6. Freight and marine insurance
- 7. Marketing expense
- 8. Social Security tax*
- 9. Ad Valorem Tax (by formula)
- 10. Occupation Tax
- 11. Federal income tax
- 12. Interest on development and working capital

* Since 1987, Social Security tax has been included under miscellaneous.

These 12 allowable expense items are deducted from the Lake Erie market value to give the estimated future income (per ton). Note that although royalty is allowable as an Occupation Tax deduction, it is not allowable on Minnesota's Ad Valorem Tax.

The present worth is then determined by multiplying the estimated future income (per ton) by the Hoskold Factor. The Minnesota Department of Revenue presently allows a 12 percent risk rate and six percent safe rate that yields the .33971 Hoskold factor when used with a 20-year life. A 20-year life has been used since 1968 as representative of the remaining life of Minnesota's natural iron ore reserves. The resulting value is considered the market value by the Minnesota Department of Revenue.

The term "class rate" was introduced for taxes payable in 1990. For 2002 and thereafter, this rate is reduced to 2.0 percent.

The tax capacity is the product of the class rate and the market value. The product of the market value and class rate must then be multiplied by the local tax rate plus the state general Property Tax rate to determine the tax. In addition, the market value times the referendum rate must be added if there is a referendum in the taxing district.

Local tax rates are a function of county, local government, and school district spending. In addition, a statewide general Property Tax levy applies to most types of property with the exception of agricultural and homestead properties. For example, for taxes payable in 2017, tax rates ranged from a low of approximately 85 percent to a high of approximately 261 percent (not including the state general Property Tax rate of 45.802 percent) in St. Louis County. The class rate from 2002–2016 has been 2 percent.

The special rate on the first $150,000 of market value that applies to class 3 commercial/industrial property does not apply to unmined iron ore that are class 5 properties.

The Minnesota Department of Revenue has tried to maintain all ores on the tax rolls, including the uneconomic, underground and unavailable classifications. A schedule of minimum rates was established in 1963 and revised in 1974, 1986, 1988, 1992 and 1999. The market values for iron ores that do not show a value with the Hoskold Formula are determined from the schedule of minimum rates. The table on the following page *(Figure 20)* lists the current schedule of minimum rates. Most of the iron ore value remaining today was determined using the schedule of minimum rates.

Open pit ores with too high of a cost to show a value with the Hoskold Formula are assigned minimum values from the open pit classification. Underground and uneconomic ores with stripping ratios exceeding five-to-one are assigned minimum values from underground uneconomic classification.

Beginning with the 1999 assessment, the minimum rates for determining market values in Crow Wing County were reduced by 50 percent. This simply recognizes that the potential for mining iron ore is substantially less in Crow Wing County than on the Mesabi Range in St. Louis or Itasca counties *(Figure 19)*.

A notice of the market value of unmined ore is sent to each person subject to the tax and to each taxing district affected on or before May 1 (M.S. 273.1104).

According to the provisions of M.S. 273.1104, a public hearing to review the valuations of unmined iron ore must be held on the first secular day following May 20. This hearing provides an opportunity for mining company and taxing district representatives to formally protest any of the ore estimates or valuation procedures they believe to be incorrect.

In addition, current conditions and future trends in the iron ore industry are discussed. Iron ore Ad Valorem taxes are expected to continue their long decline as remaining economic deposits are mined or allowed to go tax forfeit. Reserves in old flooded pits converted to recreational use are classified as underground, low-grade recreational.

Figure 20
Minimum Valuation Rates on Unmined Natural Iron Ore

	Market value/ton (cents)	
Ore Classification	**Itasca and St. Louis Counties**	**Crow Wing County**
Wash Ore Concentrate (OPC)	12.0	6.0
Heavy Media Concentrate (HMC)	9.0	4.5
Low Grade (OPPRC)	3.0	1.5
Underground Uneconomic (stripping ratio greater than 5 to 1)		
Underground Concentrate > 60% Fe (UGC)	2.4	1.2
Underground Concentrate < 60% Fe (UGC)	1.8	0.9
Underground Heavy Media (UGHM)	1.5	0.75
Low grade (UGPRC)	0.9	0.45
Low grade (UGR)	0.9	0.45

Figure 21
Ad Valorem Tax Payable on Unmined Natural Iron Ore

Year Assessed	Market Value	Payable Year	Estimated Tax Payable			Total
			Crow Wing	Itasca	St. Louis	
2007	2,255,300	2008	2,300	11,600	68,400	82,300
2008	2,345,800	2009	2,200	11,400	70,100	83,700
2009	2,347,000	2010	2,200	12,200	71,500	85,900
2010	2,345,500	2011	2,400	12,700	76,400	91,500
2011	2,341,600	2012	2,600	14,300	87,400	104,300
2012	2,485,800	2013	2,700	13,900	93,200	109,800
2013	2,492,600	2014	2,800	14,100	93,900	110,800
2014	2,501,400	2015	2,800	14,100	95,200	112,100
2015	2,490,700	2016	2,600	14,200	96,600	113,400
2016	2,476,700	2017	2,500	14,300	86,500	103,300

Ad Valorem Tax on Taconite Railroads

(M.S. 270.80 - 270.88)

Beginning with the Jan. 2, 1989 assessment, taconite railroads have been included in the definitions of common carrier railroads and were assessed and taxed on an ad valorem basis according to Minnesota law. LTV and Northshore were the only railroads classified as taconite railroads. Since the 2003 assessment, Northshore Mining is the only operating railroad.

The Minnesota Department of Revenue developed rules governing the valuation of railroad operating property. The rules have been in effect since 1979 when common carrier railroads went off the gross earnings tax. Each railroad is required to file an annual report containing the necessary information.

The valuation process utilizes the unit value concept of appraisal. For taconite railroads, this involves calculating a weighted cost indicator of value allowing for depreciation and obsolescence. Personal property is then deducted from the net cost indicator to yield a Minnesota taxable value.

This value is then apportioned to the various taxing districts where the taconite railroad owns property. The amount of value each taxing district receives is based on an apportionment formula involving three factors: land, miles of track, and the cost of buildings over $10,000.

After the market value is apportioned to each taxing district, the value is equalized with the other commercial and industrial property on a county-wide basis using an estimated median commercial and industrial sales ratio. A commercial and industrial ratio is developed for each county and applied to that county's taconite railroad market values.

Figure 22

Ad Valorem Tax Assessed on Taconite Railroads

Year Payable	Assessed	St. Louis County	Lake County	Total Tax
2007	2006	3,054	10,081	13,135
2008	2007	3,212	9,063	12,275
2009	2008	2,562	6,415	8,977
2010	2009	2,319	7,293	9,612
2011	2010	2,514	7,623	10,137
2012	2011	2,460	8,265	10,725
2013	2012	2,981	10,651	13,632
2014	2013	7,286	26,796	34,082
2015	2014	6,462	23,890	30,352
2016	2015	5,770	20,696	26,466
2017	**2016**	**4,376**	**16,224**	**20,600**

Ad Valorem Tax on Severed Mineral Interests

(M.S. 272.039, 272.04, 273.165)

Definition

Severed mineral interests are those separately owned from the title to surface interests in real estate. Each year, severed mineral interests are taxed under Minnesota law at 40 cents per acre times the fractional interest owned. The minimum tax on any mineral interest (usually 40-acre tracts or government lots) regardless of the fractional interest owned, is $3.20 per tract. No tax is due on mineral interests taxed under other laws relating to the taxation of minerals, such as unmined taconite or iron ore, or mineral interests exempt from taxation under constitutional or related statutory provisions.

Ownership of a specific mineral or group of minerals, such as energy minerals or precious metals rather than an actual *fractional interest* of all the minerals, does not constitute a fractional interest. Thus, if one individual reserved all minerals except gas, oil and hydrocarbons, and a second entity reserved the hydrocarbons, each owner would be subject to the full 40 cents per acre tax.

The Severed Mineral Interest Tax is a Property Tax that is levied by local taxing authorities in the same manner as other local Property taxes. Proceeds from the tax are distributed in this manner: 80 percent is returned by the county to local taxing districts where the property is located in the same proportion that the local tax rate of each taxing district bears to the total surface tax rate in the area; and 20 percent to the Indian Business Loan Account in the state treasury for business loans made to Indians by the Department of Employment and Economic Development.

The registration and taxation of severed mineral interests is a county function. Severed mineral interests are registered with the county recorder in the county where the interest is located. The county auditor sends a tax statement similar to any other real estate interest. The tax is normally collected in two increments payable in May and October. If the tax is less than $50, the taxpayer is required to pay in full with the May payment.

Nonpayment Penalty: Forfeiture

The eventual penalty for not paying the tax is forfeiture. Policies vary somewhat among counties. Specific questions about the tax, interest or penalties should be directed to the county recorder and auditor in the county where the minerals are located.

Tax Imposed

The tax on severed mineral interests was enacted in 1973 as part of an act that required owners to file a document with the county recorder where the interests were located describing the mineral interest and asserting an ownership claim to the minerals. The purpose of this requirement was to identify and clarify the obscure and divided ownership conditions of severed mineral interests in the state (M.S. 93.52). Failure to record severed mineral interests within time limits established by the law results in forfeiture to the state (M.S. 93.55).

History of Litigation

In 1979, the Minnesota Supreme Court ruled that the tax, the recording requirements and the penalty of forfeiture for failing to timely record were constitutional, but also ruled that forfeiture procedures were unconstitutional for lack of sufficient notice and opportunity for hearing. This decision is cited as *Contos, Burlington Northern, Inc. U.S. Steel, et al. v. Herbst, Commissioner of Natural Resources, Korda, St. Louis County Auditor, Roemer, Commissioner of Revenue, and the Minnesota Chippewa Tribe, et al., 278 N.W. 2d 732 (*1979). The U.S. Supreme Court refused to hear an appeal requested by the plaintiffs. Shortly after this decision, the legislature amended the law to require notice to the last owner of record and a court hearing before a forfeiture for failure to timely record becomes complete. Under these requirements, court orders have been obtained by the state in several counties declaring the forfeiture of particular severed mineral interests to be complete and giving title to the state.

Figure 23

Ad Valorem Tax on Severed Mineral Interests: Collection and Distribution

Period ending	80% retained by local government	20% payment to Indian Business Loan Account	Total collections of affected counties
Dec. 31, 2009	$463,472	$115,868	$579,340
Dec. 31, 2010	448,864	112,216	561,080
Dec. 31, 2011	444,016	111,004	555,020
Dec. 31, 2012	487,096	121,774	608,870
Dec. 31, 2013	452,376	113,094	565,470
Dec. 31, 2014	436,704	109,176	545,880
Dec. 31, 2015	427,756	106,939	534,695
Dec. 31, 2016	**417,991**	**104,498**	**522,489**

In 1988, the legislature amended the law to allow the commissioner of the Minnesota Department of Natural Resources (DNR)to lease unregistered severed mineral interests before entry of the court order determining the forfeiture to be complete. However, mining may not commence under such a lease until the court determines that the forfeiture is complete.

In a 1983 case, the Minnesota Supreme Court ruled that severed mineral interests owned by the Federal Land Bank of St. Paul were exempt from the state Severed Mineral Interest Tax under a federal law exempting Land Bank real estate from local Property taxes. The U.S. Supreme Court denied a petition by the State of Minnesota to review the case.

DNR Lease

If someone buys a DNR mining lease of 3 or more years duration, the Severed Mineral Interest Tax of 40 cents per acre applies. Contact the DNR, Minerals Division, to determine the status of activities under any state metallic minerals lease.

Indian Business Loan Account

The 20 percent portion of the Severed Mineral Interest Tax that is allocated to the Indian Loan Program is reported by the county auditors on the *Severed Mineral Interest Return* (SMI1). Normally, the form is submitted twice each year to correspond with payment of Property taxes.

The money deposited in the Severed Mineral Interest Account is distributed to the Indian Loan Program at the end of each month.

Department of Revenue

The processing and payment of the Severed Mineral Interest Tax is handled by the Special Taxes Division of the Minnesota Department of Revenue, Mail Station 3331, St. Paul, MN 55146-3331. Phone 651-556-4721.

Loan Program

The Indian Business Loan Program is administered by the Department of Employment and Economic Development, 1st National Bank Building, 332 Minnesota Street, Suite E-200, St. Paul, MN 55101-1351. Phone: 651-259-7424.

Taxes on Nonferrous Minerals

Companies mining or exploring for nonferrous minerals or energy resources are also subject to Minnesota taxes. This includes mining or exploring for:

- Base metals, such as copper, nickel, lead, zinc, titanium, etc;
- Precious metals, such as gold, silver and platinum; and
- Energy resources, such as coal, oil, gas and uranium.

Companies that are in the exploration stage, and not actually mining, are NOT subject to Occupation Tax or Net Proceeds Tax, however, they are subject to income taxes (e.g., regular Corporate Franchise Tax, S-Corporate Tax, etc.).

Companies that are mining nonferrous minerals are subject to the same taxes as companies that mine ferrous minerals:

- Occupation Tax (see page 23)
- Sales and Use Tax (see page 1)
- Ad Valorem Tax on severed mineral interests (see page 32)

In addition, they are subject to Ad Valorem Tax (Property Tax) in certain situations and a Net Proceeds Tax.

Ad Valorem Tax (M.S. 272–273)

Companies mining or exploring for nonferrous minerals or energy resources are subject to Property Tax the same as other businesses.

For commercial and industrial property, the assessor's estimated market value is multiplied by a class rate to obtain gross tax capacity. The first $150,000 of market value is taxed at 1.5 percent, while a 2 percent rate applies to market value over $150,000. To determine the tax, the product of the market value and class rate must be multiplied by the local tax rate plus the 45.802 percent state general Property Tax rate for taxes payable in 2017. In St. Louis County, where the majority of Minnesota's mining industry is located, the local tax rates payable in 2017 varied from a low of 85 percent to a high of approximately 261 percent. If a referendum tax is passed, the referendum rate times the full market value must be added.

If a company is mining minerals or energy resources subject to the Net Proceeds Tax under M.S. 298.015, then the following property is exempt:

- deposits of ores, metals, and minerals and the lands in which they are contained;
- all real and personal property used in mining, quarrying, producing, or refining ores, minerals, or metals, including lands occupied by or used in connection with the mining, quarrying, production, or ore refining facilities;
- and concentrate.

Net Proceeds Tax (M.S. 298.015–298.018)

The Net Proceeds Tax applies to the mining or producing of nonferrous minerals and energy resources, i.e., all ores, metals and minerals mined, extracted, produced or refined within Minnesota, except for sand, silica sand, gravel, building stone, crushed rock, limestone, granite, dimension granite, dimension stone, horticultural peat, clay, soil, iron ore and taconite concentrates.

The tax is equal to 2 percent of the net proceeds from mining in Minnesota. Net proceeds are the gross proceeds from mining less allowable deductions. Gross income from mining or producing nonferrous minerals or energy resources is calculated differently from the method used for ferrous minerals.

For **non-equity or arms-length transactions**, gross income is based on actual sales. Generally, for **non-arms-length transactions**, gross income is based on the average annual market price as published in the *Engineering and Mining Journal*.

The Net Proceeds Tax was designed to apply to mining and beneficiation, generally to the point of a saleable product. In the case of some hydrometallurgical processes, the saleable product may be a refined metal.

Deductions from the tax include only those expenses necessary to convert raw materials to marketable quality. Expenses such as transportation, stockpiling, marketing or marine insurance that are incurred after marketable ores are produced are not allowed, unless the expenses are included in gross proceeds.

Distribution of the tax. If the minerals or energy resources are mined *outside* the Taconite Assistance Area, the tax is deposited in the state's General Fund. If they are mined or extracted *within* the Taconite Assistance Area, the tax is distributed to:

- Cities and towns (5%), counties (20%), and school districts (10%) where the minerals or energy resources are mined or extracted, or where the concentrate is produced. If concentrating occurs in a different taxing district from where the mining occurs, 50 percent is distributed to the taxing districts where mined and the remainder to those districts where processed. In addition, counties must pay 1 percent of their proceeds to the Range Association of Municipalities and Schools.
- Regular School Fund (20%)
- Taconite Municipal Aid Account (10%).
- Taconite Property Tax Relief (20%), using St. Louis County as fiscal agent.
- Iron Range Resources & Rehabilitation (5%).
- Douglas J. Johnson Economic Protection Trust Fund (5%).
- Taconite Environmental Protection Fund (5%).

Distributions are made annually on July 15; however, there are currently no companies subject to the Net Proceeds Tax.

Glossary of Terms

Acid pellets — Taconite pellets comprised of iron, oxygen and silica held together by a binder such as bentonite (clay) or peridor (organic).

Agglomeration — The term describing the preparation and heat treatment used to prepare iron ore pellets or other iron ore products for shipment and use in a blast furnace.

Arms-length transaction — A sale of iron ore or pellets representing a true free market transaction when the buyer normally does not have an ownership or other special relationship with the seller.

Basic oxygen furnace (BOF) — A steel-making furnace invented in Austria. It replaced open hearth furnaces in the 1960s. It is currently the standard furnace used by the integrated steel producers in the United States.

Beneficiation — The process of improving the grade by removing impurities through concentrating or other preparation for smelting, such as drying, gravity, flotation or magnetic separation. In taconite operations, this includes the first stage of magnetic separation and converting the concentrate into taconite pellets for use in making steel.

Concentrate — The finely ground iron-bearing particles that remain after separation from silica and other impurities.

Douglas J. Johnson Economic Protection Trust Fund (DJJ) — A portion of Production Tax revenues is allocated to this fund with the intent to use the funds to diversify and stabilize the long-range economy of the Iron Range.

Direct reduced iron (DRI) — A relatively pure form of iron (usually 90 percent + Fe), which is produced by heating iron ore in a furnace or kiln with a reducing agent such as certain gases or coal.

Dry weight — The weight of iron ore or pellets excluding moisture. For pellets, the dry weight is normally 1 to 2 percent less than the natural weight.

Electric Arc Furnace (EF or EAF) — A furnace in which an electric current is passed through the charge. These furnaces are much smaller than the conventional BOFs used by the integrated steel producers.

Fe unit — Commonly referred to as an iron unit. An iron unit is a term of measurement denoting one ton containing one percent iron. Iron ore and taconite produced in the United States is measured in long tons (see definition). One long ton of taconite containing 65 percent iron also contains 65 long ton iron units.

Historically, this measurement was and is used for the selling price quoted in cents per iron unit. One example is a currently published price of acid pellets FOB mine at 37.344 cents per dry gross ton iron unit *or* $.37344 per iron unit.

Fluxed pellets — Taconite pellets containing limestone or another basic flux additive. Fluxed pellets eliminate the need to add limestone in the blast furnace, improving productivity and quality. Adding flux reduces the iron content of a pellet. Fluxed pellets, as used in this guide, mean pellets containing two percent or more limestone or other flux.

Partially fluxed pellets — Fluxed pellets containing 1.99 percent or less limestone or other flux additive.

Gross Domestic Product Implicit Price Deflator (GDPIPD) — An index maintained by the U.S. Department of Commerce measuring inflation in the overall economy. The Production Tax rate is adjusted annually based on the change in this index.

Integrated steel producer — Term used to describe steel companies that produce steel by starting with raw iron ore, reducing it to molten iron in a blast furnace, and producing steel with a BOF, open hearth, or electric furnace.

Lake Erie value — The traditional and quoted price of iron ore from the earliest days of iron ore mining in Minnesota and Michigan. This price per iron unit included delivery, mainly rail and lake transportation, from the mine to a Lake Erie port.

This was the starting point for Occupation Tax since its 1921 beginning. It was the standard method of pricing domestic iron ore and taconite for Occupation Tax until the mid-1980s (see Mine Value).

Long ton — The standard unit for weighing iron ore and taconite in the United States. A long ton equals 2,240 pounds.

M.S. 298.225 — A Minnesota statute (law) guaranteeing the Production Tax aids received by municipalities, counties, schools and the Iron Range Resources & Rehabilitation. The aid levels are adjusted according to a sliding scale based on production levels.

Metric ton — Standard unit for weighing iron ore and taconite in most areas of the world. A metric ton equals 1,000 kilograms or 2,204.62 pounds.

Mine value — The value of iron or pellets at the mine. This became the starting point for Occupation Tax in 1987. This value per iron unit does not include any rail or lake transportation beyond the mine.

Mini mill — A small steel mill using an electric furnace that produces steel from scrap iron.

Natural ore — Iron ore that can be fed to a blast furnace with less complicated processing than taconite requires. Natural ore typically contains 50 percent +Fe (iron) in its natural state.

Natural weight — The weight of iron ore or pellets including moisture.

Net proceeds tax — A tax equal to two percent of net proceeds from mining. Net proceeds are determined by subtracting certain basic deductions such as labor, equipment, supplies and depreciation from gross proceeds or sales.

Non-equity sales — See Arms-length transaction.

Pellet chip — Broken pellets often cannot be sold as pellets and instead are sold at a reduced price for sinter plants and other uses. For Occupation Tax purposes, chips are defined as individual shipments or stockpiles containing at least 85 percent of pellet chips smaller than one-fourth inch. Such chips cannot be shipped or commingled with regular pellets.

For Occupation Tax purposes, pellet chips are valued at 75 percent of the value of the unbroken pellets.

Percentage depletion — A taxable income deduction in the form of an allowance representing a return on capital investment on a wasting asset subject to a gradual reduction in reserves. This deduction applies to income derived from various mining or oil and gas properties.

Range Association of Municipalities and Schools (RAMS) — An association representing Iron Range cities, towns and schools receiving any funding from the Production Tax.

Region 3 — Koochiching, Itasca, Aitkin, Carlton, St. Louis, Lake and Cook counties.

Royalty — A share of the product or profit reserved by the owner for permitting another to use the property. A lease by which the owner or lessor grants to the lessee the privilege of exploring, mining and operating the land in consideration of the payment of a certain stipulated royalty on the mineral produced.

Short ton — Standard for weighing many commodities in the United States. It equals 2,000 pounds.

Steel Mill Products Index (SMPI) — A United States government index tracking the actual selling price of all steel products in the United States. This index is published monthly by the U.S. Department of Labor. It is part of the formula used to determine a product value for Occupation Tax purposes each year.

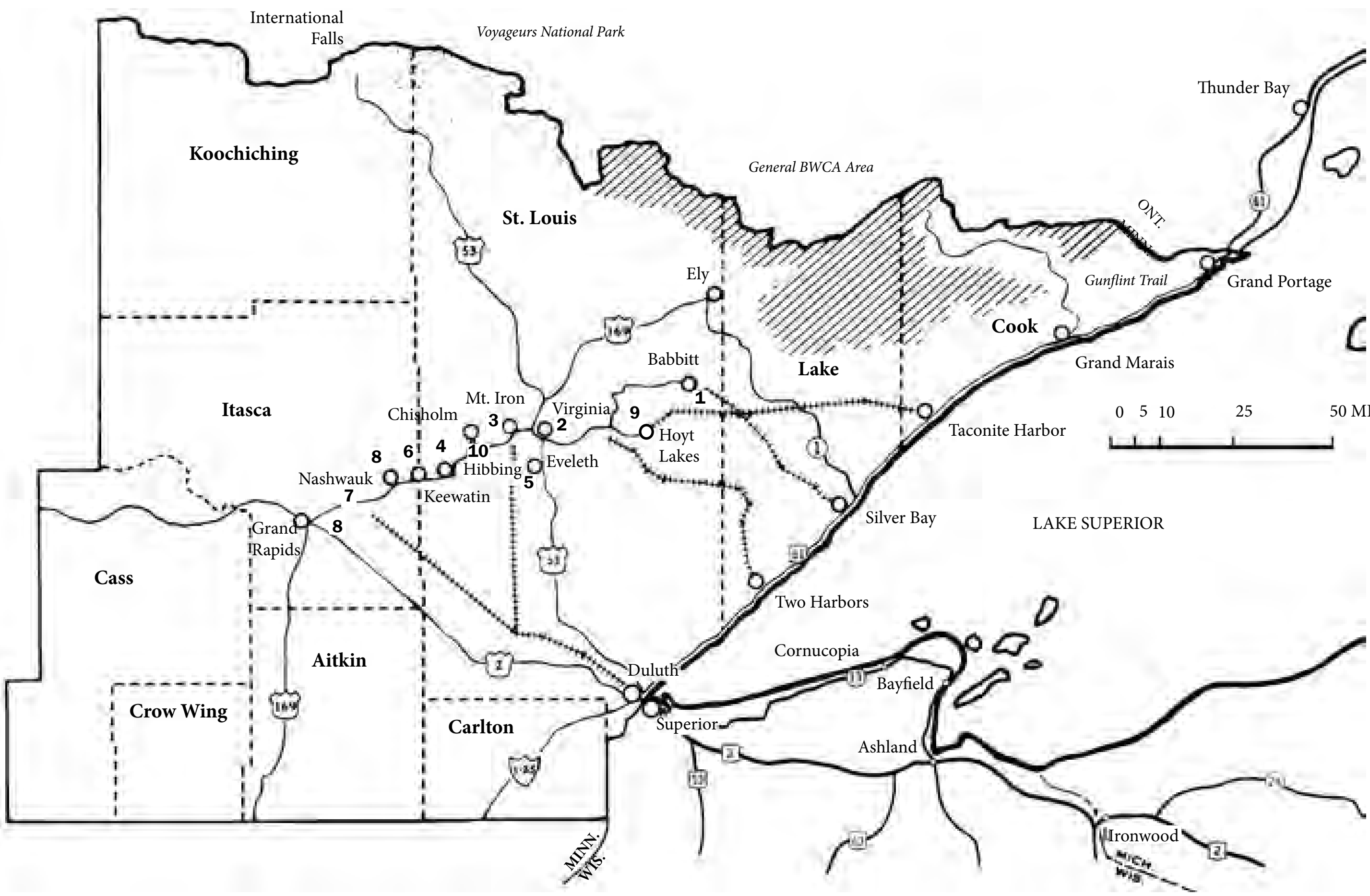
Taconite — Ferruginous chert or ferruginous slate in the form of compact, siliceous rock in which the iron oxide is so finely disseminated that substantially all of the iron-bearing particles are smaller than 20 mesh.

It is not merchantable in its natural state, and it cannot be made merchantable by simple methods of beneficiation involving only crushing, screening, jigging, washing and drying or any combination thereof. (MS 298.001, subd. 4)

Tailing — Small rock particles containing little or no iron, which are separated during various stages of crushing, grinding, and concentration. Most of the separation is done with magnetic separators. Silica is the main mineral constituent of tailings.

Taxable tons — The three-year average of the current and prior two years production. The Production Tax is based on taxable tons. The weight is on a dry basis without any flux additives. For other iron bearing material subject to the Production Tax, only the current year is used.

Mine Locations and Production Capacity



		Effective Capacity* (million tons)
1.	**Northshore Mining** Owner: Cleveland-Cliffs, Inc. (100%)	6.2
2.	**ArcelorMittal Minorca Mine** Owner: ArcelorMittal (100%)	2.8
3.	**U. S. Steel–Minntac** Owner: USS Corporation (100%)	16.0
4.	**Hibbing Taconite** Cliffs-Cleveland Inc., Managing Agent Owners: ArcelorMittal (62.3%) Cleveland-Cliffs, Inc. (23%) U. S. Steel Canada (14.7%)	8.0
5.	**United Taconite LLC** Owner: Cleveland-Cliffs, Inc.(100%)	5.4

		Effective Capacity* (million tons)
6.	**U. S. Steel–Keewatin Taconite** Owner: USS Corporation (100%)	6.0
7.	**Former Essar Steel Site**	Unknown
8.	**ERP Iron Ore** Owner: ERP Iron Ore LCC (100%)	3.0
9.	**Mesabi Nugget LLC** Owners: Steel Dynamics, Inc (81%) Kobe Steel, Ltd (19%)	0.5
10.	**Mining Resources LLC** Owner: Steel Dynamics, Inc. (100%)	1.0

* Effective capacity is the annual production capacity in natural long tons (including flux) that can be sustained under normal operating conditions.

The ownership percentages shown are the ultimate percentages controlled by parent steel and mining companies.
In some instances, various other partnerships and subsidiaries are listed on legal corporate documents.

Distribution of Mining Taxes
Production Year 2016 Tax Obligations - $88,560,123

$96,516,727*	$5,059,196	($13,958,786)**	$942,986***	None
Production Tax	**Occupation Tax**	**Sales and Use Tax**	**Various Ad Valorem and Property taxes**	**Net Proceeds Tax**

Production Tax

- Cities and townships
- School districts
- Counties
- Iron Range Resources & Rehabilitation
- Miscellaneous

Occupation Tax

- State General Fund 50%
- Elementary and secondary education 40%
- University of Minnesota 10%

Sales and Use Tax

- State General Fund 100%

Various Ad Valorem and Property taxes

- Cities and townships
- School districts
- Counties
- Indian Affairs Council

These taxes are related to "Property Tax." They are paid to the county in which the property is located and then distributed proportionately among the counties, cities, townships and school districts.

***Taxes included:

-Tax on unmined taconite	$296,597
-Ad Valorem Tax on natural iron ore	103,300
-Ad Valorem Tax on taconite railroads	20,600
-Tax on severed mineral interests	522,489
	$942,986

Payable 2017, except severed minerals are payable 2016

Net Proceeds Tax

Within Taconite Assistance Area

Distribution to local governments, schools and IRRRB funds similar to the Production Tax

Outside Taconite Assistance Area

State General Fund 100%

No minerals subject to this tax are currently mined.

* Includes $7,375,366 appropriation from the State of Minnesota General Fund.

**The 2016 Sales and Use Tax number is affected by a law change that occurred mid 2015. Manufacturers no longer pay Sales and Use Tax on equipment used in the production process. As a result of this change, we refunded more Sales and Use Tax than we collected.