TACONITE IRON MINING IN WISCONSIN: A REVIEW

Cory McDonald[1], Brandy Baker-Muhich[1], Tom Fitz[2], Paul Garrison[1], Jordan Petchenik[1], Paul Rasmussen[1], Robert Thiboldeaux[3], William Walker[1], and Carl Watras[1]

19 December, 2013

[1] Wisconsin Department of Natural Resources, Bureau of Science Services

[2] Department of Geology, Northland College

[3] Wisconsin Department of Health Services, Bureau of Environmental and Occupational Health

TABLE OF CONTENTS

List of Figures ii
List of Tables ii
Environmental Summary iii

1. Introduction 1
  1.1. History of iron mining in Wisconsin 1
  1.2. Geology of Iron-bearing Formations 3
  1.3. The Taconite Mining Process 9
2. Environmental and Ecological Considerations 14
  2.1. Hydrology 15
  2.2. Potential Pollutants 18
  2.3. Aquatic Ecology 31
3. Human Health Considerations 32
  3.1. Health Risks Related to Air Quality 32
  3.2. Health Risks Related to Drinking Water Quality 34
  3.3. Potential Impacts on Food Safety and Availability 37
4. Socioeconomic Considerations 38
  4.1. Sociocultural Considerations 38
  4.2. Economics 43
5. Water Quality Monitoring 52
  5.1. Objectives 52
  5.2. Monitoring Design 52
  5.3. Analysis 54
  5.4. Groundwater Monitoring 54
6. Laboratory Methods 56
  6.1. Toxicity Analysis 57
  6.2. Waste Characterization 59
7. Annotated Bibliography 60

Appendix A: Resources for Methods of Social Inquiry 92
Appendix B: Equivalence Tests 94
Appendix C: Overview of relevant analytical methods 95

FIGURES

Figure 1. Historical iron mining activities in Wisconsin and additional known iron ore reserves 1

Figure 2. Reclaimed site of the former Jackson County iron mine near Black River Falls, WI.. 3

Figure 3. Aeromagnetic map of Wisconsin 5

Figure 4. Geologic cross section of the Penokee Range near Upson, Wisconsin 7

Figure 5. Drilling operations in preparation for surface blasting at the Minntac mine 9

Figure 6. The Empire and Tilden mine pits near Ishpeming, MI..10

Figure 7. Schematic of taconite mining process..11

Figure 8. Tailings basin at Keetac (Keewatin, MN)..12

Figure 9. Major watersheds adjacent to the Penokee-Gogebic Iron Range..15

Figure 10. Simplified diagram of potential hydrologic alterations associated with the various stages of a taconite mining operation..16

Figure 11. Average concentrations of sulfate in the St. Louis River watershed 21

Figure 12. Percentage of mercury releases from different sectors in the Lake Superior basin............22

Figure 13. The aquatic mercury cycle in a representative Wisconsin lake 25

Figure 14. Theoretical relationship between mercury methylation rate (MMR) and two key substrates, inorganic mercury and sulfate..26

Figure 15. An array of humidity cells in the rinsing phase and an individual humidity cell containing greenstone rock...58

TABLES

Table 1. Water resources within the Gogebic District of northern Wisconsin 14

Table 2. Sulfide minerals detected in more than one sample from the Tyler formation........................ 19

Table 3. Annual mercury emissions attributable to taconite processing in nine facilites in northeastern Minnesota 23

Table 4. Hg concentrations (ng g^{-1}) from taconite mining operations in Minnesota................................ 24

Table 5. Municipalities near the Penokee Range.. 46

Table 6. Bad River Reservation Census Designated Places.. 46

Table 7. Personal Income by Sector, Ashland County, 2001 and 2011 47

Table 8. Wisconsin Natural Resources State Statutes and Administrative Codes relevant to taconite mining.. 56

ENVIRONMENTAL SUMMARY

The majority of historical iron mining activities in Wisconsin involved the removal of high-grade (direct-shipping) ore, which was mined in several areas throughout the state. The major remaining deposits are taconite, a low-grade (typically 20-30% iron) ore that requires processing to increase the iron content and remove impurities. The most significant of these deposits is located in the Penokee-Gogebic district in northern Wisconsin

Hydrology

Mine pits spanning multiple watersheds or aquifers can potentially alter downstream hydrologic regimes via inter-basin transfer of water. Evapotranspiration, runoff, and infiltration can all potentially be altered by mining activities, and such effects can be expected to evolve over time as operations progress. Open-pit mines must typically employ dewatering wells which produces a large local cone of depression. The effect of dewatering activities on regional groundwater levels/flows and stream baseflow is dependent on the local groundwater hydrology, aquifer characteristics, and discharge locations.

Constituents of concern

There are number of potential pollutants (predominately, though not exclusively, related to water quality) associated with open-pit taconite iron mining. These include:

- *Acid Mine Drainage.* When sulfide minerals are exposed to oxidizing conditions (e.g., brought to the surface and exposed to oxygen and water), sulfuric acid is produced. This acid release has the potential to reduce pH, deposit precipitates, and mobilize metals in downstream water resources. Pyrite and other iron sulfides are a commonly encountered minor constituent in the rocks of the Penokee Range, and pyrite has also been found to be abundant (20%) at some locations. However, acid mine drainage is a complex function of a number of geochemical and environmental factors, and the potential for it occurring at a given site is best assessed using laboratory methods (e.g., humidity cells) that simulate chemical weathering.

- *Metals.* Many metals are toxic to organisms at elevated concentrations and some metals bioaccumulate in aquatic food webs. Aquatic organisms are often particularly sensitive to metal pollution. Because trace metals often occur as impurities in mineral formations, metals of concern are also best identified using simulated chemical weathering. Aluminum is of particular interest, as it is abundant in the Ironwood formation and has been linked to fish mortality in acidified waters. Magnetite taconite also commonly contains Mg, Ti, V, Cr, Mn, Co, Ni, Cu, Hg, and Zn.

- *Mercury.* Taconite processing is often a major source of mercury emissions, released primarily during the induration process (heating of taconite pellets). Historically, mercury emissions to the atmosphere were considered to be widely dispersed. Recent studies suggest, however, that local and regional deposition is more important than previously thought. Mercury methylation (methylmercury is the form taken up by organisms) and bioaccumulation occurs in the aquatic environment. Elevated concentrations in fish tissue are a well-documented human health concern.

- *Sulfate.* Sulfate, which can potentially be leached from mine tailings and waste rock, plays a role in the production of acid mine drainage and also has a stimulatory effect on methylmercury production in the environment. There is some evidence that elevated sulfate concentrations in surface waters is toxic to wild rice, and Minnesota has a 10 mg/L sulfate standard for its protection. Minnesota is currently in the final stages of a two-year in-depth study on the effects of sulfate on wild rice, and may revise their standard based on the results.

- *Selenium*. Selenium is geochemically similar to sulfur, and thus is expected to occur in small amounts in sulfide minerals (and may be similarly released due to chemical weathering). Selenium is highly bioaccumulative, and thus dissolved concentrations are not reliable indicators of potential selenium environmental toxicity. Selenium pollution has been documented and is being addressed at the taconite iron mines in Michigan.

- *Mineral fibers*. The iron formations of Wisconsin contain fibrous amphibole minerals, and asbestiform grunerite has been found at the site of the proposed Gogebic Taconite project.). The Northshore mine on the Eastern end of Minnesota's iron range is also a documented source of several amphibole minerals. Asbestos is a human health hazard; extended exposure to airborne fibers can cause mesothelioma and other cancers.

- *Nutrients.* The rock present in the Penokee-Gogebic contains a relatively large concentration of phosphorus (the phosphorus content of the iron-bearing formation is approximately 660 mg of phosphorus per kg of rock.). Weathering of waste rock and processing of ore may liberate phosphorus, which is the primary driver of eutrophication in Wisconsin's surface waters.

- *Suspended solids.* Taconite processing produces a large amount of fine-grained rock. This and other mine-site characteristics (e.g., increased cover of impervious surfaces) have the potential to increase downstream turbidity.

- *Organic compounds*. While potential pollutants associated with the ore and waste rock are typically of greater concern due to the large volume of these materials processed, a number of fuel, lubricants, solvents, and process chemicals are also used on site, and may potentially be present in stormwater or process water outfalls.

SPECIFIC CONSIDERATIONS

Based on the information presented in this report, baseline and ongoing environmental monitoring at a taconite mining operation should take into account the following:

- Quantification of all components of the hydrologic budget in affected watersheds, including continuous monitoring of surface and groundwater flows and elevations, is necessary to identify hydrologic alterations associated with mining activities.

- Measurement of the above-listed water quality parameters (in addition to routine parameters such as pH, alkalinity, conductivity, dissolved oxygen etc.) in surface and groundwater can characterize baseline conditions and identify any changes associated with mining activities. Regular sampling (e.g., monthly), as well as high-flow (event-driven) sampling is necessary to detect constituents that may be traced to a continuous source (e.g., leached metals in groundwater) as well as those that may increase in concentration during storm events (e.g., particle-bound selenium).

- Sampling sites are typically located on streams above and below a mining site. Monitoring wells are often concentrated downgradient from the site, with fewer located upgradient. Affected lakes are generally sampled at inflows and at the deepest locations (deep lakes should also be vertically sampled during stratification).

- Initially, intensive monitoring may be required to establish the natural variability in the parameters being measured; sampling frequency may be reduced for ongoing monitoring. Similarly, many monitoring wells may initially be required to establish local groundwater flow patterns. These may also be reduced in number for ongoing monitoring.

- Biosurveys can characterize aquatic communities upstream and downstream from mining activities. Wild rice should also be inventoried in potentially affected areas, given the current uncertainty regarding the impact of sulfate and other contaminants on this resource. Whole-effluent toxicity (WET) testing is routinely performed on process outfalls; given the potential for mining-related contaminants to be present in runoff, WET may be appropriate for stormwater or holding pond outfalls as well. Further, selenium and mercury, which bioaccumulate, should be measured in fish tissue, sediment, and fish and bird eggs, rather than measuring only dissolved concentrations.

- Duplicating baseline characterization and monitoring in at least one reference (unaffected) watershed in the region allows hydrologic and water quality variability due to sources other than mining activities (e.g., variability in precipitation) to be clearly identified.

- Mine waste is typically assessed for acid mine drainage and leaching potential using a humidity cell test. It is important to note that samples have been observed to produce neutral drainage for as long as 14 years before producing acidic drainage, so these tests should be run indefinitely. Due to the heterogeneous distribution of sulfide minerals in the Penokee Range, additional waste characterization tests would ideally be initiated as the mine pit develops.

- In order to make quantitative predictions of potential mercury emissions and local deposition, its concentration in a number of media should be considered, including process waters and discharges, storm water, ore, tailings, and pellets (green and fired), as well as stack emissions.

1. INTRODUCTION

1.1. HISTORY OF IRON MINING IN WISCONSIN

Iron mining has more than a 150-year history in Wisconsin. Early mining activities in the state were primarily located in the Upper Mississippi River zinc-lead (Zn-Pb) district in the southwestern portion of the state (Grant, Lafayette, and Iowa counties, Figure 1). Major mining activities in this region began in the 1820s, initially focusing on lead, and then also on zinc beginning around 1860. Mines were typically underground. Major ores mined in this region were lead sulfides and zinc carbonates and sulfides. However, iron sulfides (primarily marcasite) were also present and were recovered by magnetic separation where sufficiently abundant (Grant 1903), and thus these were the earliest large-scale iron mining operations in the state.

Iron mining in the Mayville District (Dodge County) began in the mid-1800's (Figure 1). The Iron Ridge Mine operated from 1849 through 1914, and the Mayville Mine operated from 1892 through 1928 (USGS 2005). These were both surface and underground mines. The Mayville Mine produced over 2 million tons of ore, while the Iron Ridge Mine produced another 200,000 tons.

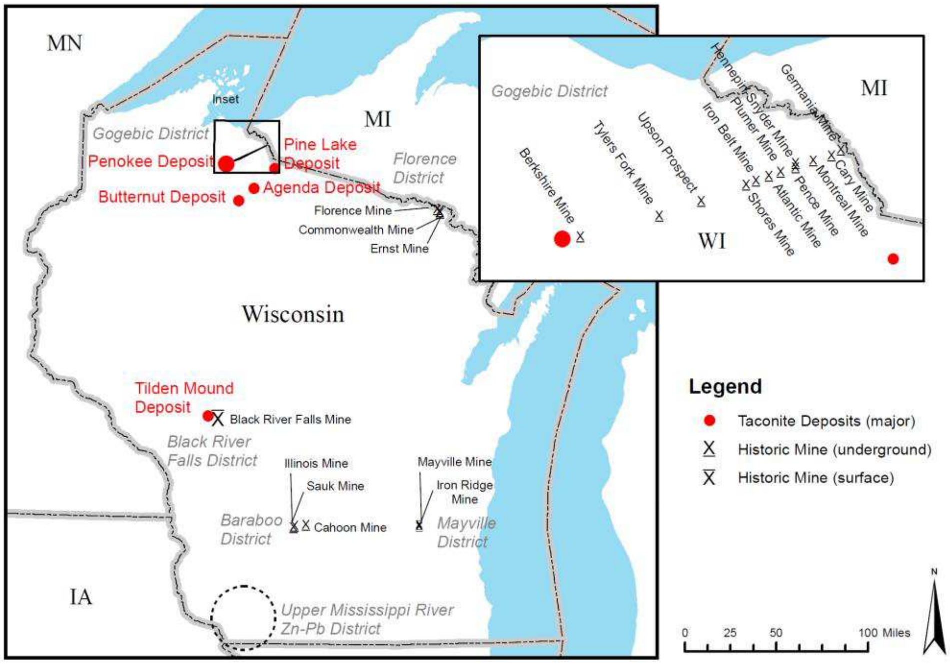


FIGURE 1. HISTORICAL IRON MINING ACTIVITIES IN WISCONSIN (NATURAL IRON ORE, WITH THE EXCEPTION OF THE BLACK RIVER FALLS TACONITE MINE AND IRON SULFIDES MINED IN LIMITED QUANTITIES IN THE UPPER MISSISSIPPI RIVER ZINC-LEAD DISTRICT) AND ADDITIONAL KNOWN IRON ORE RESERVES (EXCLUSIVELY TACONITE ORE). SEE TEXT FOR DATA SOURCES.

The Baraboo district, located in Sauk County, was an active iron mining center in the early 1900s (Figure 1). The Illinois (1904-1916), Cahoon (1916-1925), and Sauk Mines (dates unknown) operated in this region (USGS 2005). These were underground operations. The Illinois Mine shipped 315,000 tons of Bessemer (low-phosphorus, typically below 0.045%) ore, while the Cahoon Mine shipped 328,000 tons of non-Bessemer ore.

Beginning in 1880, the portion of the Menominee Iron range that extends into Wisconsin in the Florence district (Florence County) was also home to several underground mines: the Florence (1880-1931), Ernst (1914-1929), and Commonwealth (1880-1916) mines (USGS 2005) (Figure 1). Over 7 million tons of non-Bessemer ore shipped from this region. At least two additional prospects were explored in the region: the Larson Exploration (Jackson County Iron Mining Company) in 1948 and the LaSalle Falls sulfide deposit (Great Lakes Exploration) in 1969 (USGS 2005).

The most concentrated region of historical iron-mining activity in the state was the Gogebic district, along the Penokee Range in northern Wisconsin (Ashland and Iron counties, Figure 1). The Penokee iron-bearing series extends from Lake Gogebic in Michigan on the eastern end to Namekagon Lake in Sawyer County on the western end (Irving and Van Hise 1892). This deposit was first documented in 1848, and large-scale mining began in the 1880s. The earliest mines operating along this formation were located in Michigan, but beginning in the mid-1880s at least a dozen underground mines were developed along the Wisconsin portion of the district, some continuing to mine high-grade iron ore as recently as the 1960s. These included, from east to west: the Germania (1885-1912), Cary (1886-1965), Montreal (1886-early 1960s), Hennepin-Snyder (1888-1906), Pence (1888-1912), Plummer (1912-1932), Atlantic (1887-1913), Iron Belt (1888-1912), Shores (1896-1899), Upson (prospect; 1902-1903), Tyler's Fork (prospect; 1890 and 1902-1903), and Berkshire Mines (1922-1924) (USGS 2005). Ores from these mines contained 50-60% iron, 0.03-0.06% phosphorus (i.e., Bessemer and non-Bessemer), and contained varying amounts of manganese (Irving and Van Hise 1892). Production figures are not available for all of these mines, but well in excess of 14 million tons of ore shipped from the region (USGS 2005).

The most recently active iron mine in Wisconsin was in the Black River Falls district in Jackson County. Previously, an iron mine had been in operation at the Tilden Mound deposit from 1856 through 1892 (USGS 2005). In 1969, the Jackson County Iron Company (a subsidiary of the Inland Steel Company) opened the Black River Falls taconite mine at the Seven Mile Mound deposit. Ore mined at this location was primarily magnetite taconite (Section 1.2), with an iron content of 25-40% (Marsden 1978). Mining activities at this site ceased in 1982. Nearly 11 million tons of taconite pellets shipped from this mine during its operation (USGS 2005). At the time of closure, the mine pit covered 146 acres and was 385 feet deep, and the mining works (waste-rock dumps, tailings disposal, etc.) covered approximately another 1,000 acres. The pit has been allowed to fill with water and is now known as Lake Wazee, while the surface areas have been resloped and revegetated (Applied Ecological Services, Inc. 2008). An aerial view of the site today is shown in Figure 2. A similar, but smaller, magnetite taconite deposit exists at Tilden Mound, but its proximity to the Black River and the city of Black River Falls present obstacles to developing a mine at this location (Marsden 1978).

REMAINING IRON ORE DEPOSITS IN WISCONSIN

Several taconite type deposits remain in addition to Tilden Mound. These are all located in the vicinity of the Gogebic district in Ashland and Iron counties. The most significant is the Penokee Deposit, approximately defined by the locations of historical mines in the district (Figure 1), with the area of most interest being located in the west-central portion of the range in the vicinity of the former Berkshire Mine. Marsden (1978) described these reserves as "the largest in Wisconsin and one of the more important undeveloped iron ore reserves of the United States." He estimated total reserves in this region to be 3.7 billion metric tons of crude ore with a 32% weight recovery. About 75% of this ore is located in Ashland County. This ore is magnetite taconite, with a crude iron content of 20-35%. Gogebic Taconite, LLC has recently expressed interest in developing a surface mine at this location, with initial operations to be located between Mellen and Upson.

At least three additional magnetite taconite deposits with production potential exist in Ashland and Iron Counties (Marsden 1978). These are, from east to west, the Pine Lake deposit (estimated 206 million tons of crude ore with 27% weight recovery) the Agenda deposit (estimated 160 million tons of crude ore with 28% weight recovery), and the Butternut deposit (estimated 53 million tons of crude ore with a 29% weight recovery). A mine was planned at the Butternut deposit by the Ashland Mining Company in the late 1950s (Kohn 1958), but never opened. Some additional exploration was carried out in the region throughout the 20th century, with rock from at least one site (near Moose Lake in Iron County, drilled by American Can Company) containing 20-31% iron (USGS 2005).

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

FIGURE 2. RECLAIMED SITE OF THE FORMER JACKSON COUNTY IRON MINE NEAR BLACK RIVER FALLS, WI. THE CIRCULAR AREA NEAR THE TOP OF THE IMAGE WAS THE TAILINGS POND; LAKE WAZEE (CENTER) WAS THE MINE PIT.

1.2. GEOLOGY OF IRON-BEARING FORMATIONS

The most common and voluminous iron-rich deposits of Wisconsin are the Precambrian "Lake Superior-type" sedimentary iron formations. The iron-bearing rocks of the Baraboo District, Black River Falls District, the Florence District in Northeastern Wisconsin, and those of the Penokee-Gogebic Range in Northern Wisconsin are all of this type. The iron-rich deposits of the Upper Mississippi River Zn-Pb District and the Mayville District are "Phanerozoic-type" deposits that occur in younger rocks with different mineralogy and geologic settings than the Lake Superior-type iron deposits. The Lake Superior-type deposits contain the largest reserves of iron and are the only deposits currently being mined in the Lake Superior iron ranges. The Phanerozoic-type deposits in the Upper Mississippi and Mayville Districts are smaller, so this discussion focuses on the geology of the Superior-type deposits.

There are other iron-rich rocks in Wisconsin that are not considered iron ores because of their relatively low concentration of iron in comparison to the Lake Superior-type and Phanerozoic-type deposits – specifically the iron-rich mafic igneous rocks of Mid-continent Rift of Northern Wisconsin, just north of the Penokee-Gogebic Range. Although these rocks have lower concentrations of iron, the total volume of iron is huge because of the large volume of these igneous rocks, thus the rocks show clearly on the magnetic map of the state (Figure 3). The magnetic intensity is controlled primarily by the concentration of iron oxide minerals, so the size and structure of iron ranges can be discerned. The iron-rich igneous rocks of the Mid-continent rift also stand out clearly in contrast to surrounding rocks with lower iron concentrations. Aeromagnetic studies have been especially useful in delineating the size and structure of the poorly exposed iron formations in northeastern Wisconsin.

The Lake Superior-type deposits are bedded sedimentary rocks that consist predominantly of iron oxides, primarily hematite and/or magnetite; and microcrystalline quartz in the form of chert or jasper. The ratio of iron oxides to quartz varies along a continuum from nearly 100% iron oxide in iron formations, to rocks that are about half iron oxides and half quartz, referred to as "banded iron formation", or "BIF"; to rocks that are composed of nearly 100% microcrystalline quartz or jasper, commonly referred to as "jaspilite." Various types of iron formations and banded iron formations are common in the Lake Superior Region, but only those that have the highest proportion of iron oxide minerals are potentially economic deposits – these rocks are commonly referred to as "taconite". The taconite deposits of the Lake Superior region contain large amounts of potentially economic ore, particularly in the Gogebic-Penokee Range. Hematite, magnetite and quartz are the dominant minerals in these deposits. Other minerals that commonly occur in taconite are siderite, stilpnomelane, chlorite, chamosite, pyrite, and accessory minerals typically in trace amounts. The proportions of pyrite, siderite, and carbonate minerals other than siderite are important in influencing the acid-generating and neutralizing capacity of mining waste materials (Section 2.2).

In some areas within the Lake Superior-type iron formations, geologic processes concentrated the iron into relatively soft hematite-rich zones that were especially high-grade economic iron ores. These zones are referred to as "natural ore" and were the target of much of the early mining in the Lake Superior-type iron deposits. The ore zones were relatively small in comparison to the larger, harder, lower-grade taconite deposits they occur within. Since the zones of natural ore were small and discontinuous, the mining of these deposits was accomplished in relatively small surface pits and in underground workings. Much of the natural ore was depleted by the time underground iron mining ended in 1967 in the Penokee-Gogebic Range. Since that time, techniques have been developed to mine and process the larger, harder, lower-grade taconite deposits which are the source of nearly all iron ore in the world today. The taconite requires beneficiation (Section 1.3), typically being concentrated into taconite pellets prior to shipping, unlike the original high-grade natural ores which were shipped directly from the mines to steel mills.

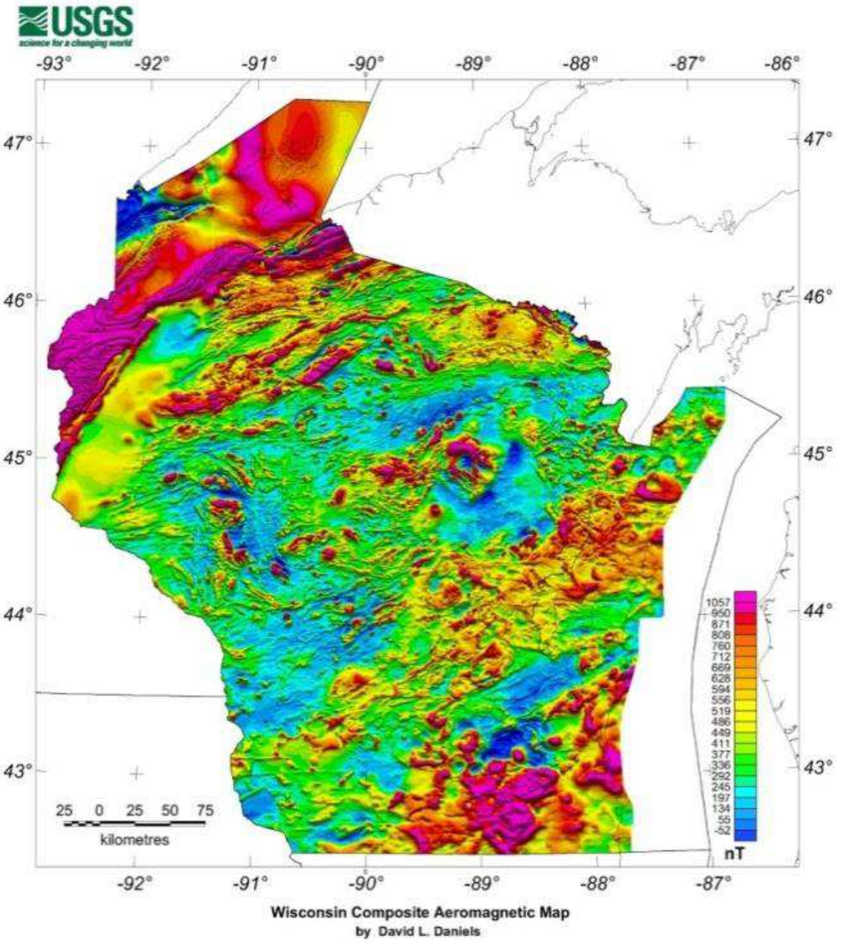


FIGURE 3. AEROMAGNETIC MAP OF WISCONSIN (DANIELS AND SNYDER, 2002)

The mineralogy of taconite deposits, like that of any rock unit, is variable both vertically with stratigraphic position and also laterally along the strike of the deposits. Much of the variability is owing to the heterogeneity of the original deposit at the time of deposition, whereas other variations are the result of the geologic history since deposition. Metamorphism is one way in which the mineralogy has been changed in some iron formations of Wisconsin. Metamorphosed iron formations often contain mineral assemblages unlike those in unmetamorphosed rocks. These high-temperature minerals include members of the olivine, pyroxene, and amphibole groups. Some of the amphibole minerals can have an asbestiform habit and may pose health hazards (Sections 2.2 and 3.1).

The Lake Superior-type iron formations of the Upper Midwest were all deposited during Neoarchean to Paleoproterozoic time, probably under similar geological conditions, so there are many similarities between them. This allows general comparisons of the rock to be made between the iron formations of Wisconsin and those in Michigan and Minnesota. However, there are still differences in geology and composition between the different deposits and even within each deposit, such that a site-specific geochemical characterization is necessary to identify potential pollutants associated with mining activities. For example, all the Superior-type deposits are dominated by iron oxides and quartz, but the amount of pyrite can vary greatly within each formation. An accurate understanding of the mineralogy and geochemistry of the ore deposits and adjacent rocks is necessary to determine if asbestiform minerals are present, to evaluate the acid-generating and neutralizing potential of the rocks, and to determine what elements may be mobilized during weathering of waste rock piles (Section 2.2).

Lake Superior-type iron formations have prominent bedding defined by variations in mineralogy of adjacent beds and parallel planes of weakness. The bedding is typically either planar or wavy on a relatively small scale, but in either case constitutes an important structural feature that influences the stability of mine workings and act as preferential groundwater flow paths. In most of the iron districts of Wisconsin the rocks have been deformed so that originally horizontal bedding dips into the Earth, often very steeply. This dip angle influences the amount of potential ore rock that is near the surface and the amount that is more difficult to access, which in turn influences the amount of overburden rock that would end up as waste during mining. In open-pit mining, progressively more overburden waste rock must be removed as the mine advances downward. Additionally, the angle of dip influences the stability of slopes in and around a mine.

IRON-BEARING FORMATIONS OF WISCONSIN

Mayville and Mississippi Valley Districts

The iron-bearing formations of the Mayville and Mississippi Valley Districts are Phanerozoic-type iron deposits rather than Superior-type deposits. The Mayville ores were iron-rich oolitic rocks containing goethite, hematite, calcite, dolomite, siderite, halloysite, and leverrierite layered between carbonate and shale units. The ore zone varies from trace to 55 feet in thickness (Hawley and Beaven 1934).

Baraboo District

The Freedom Formation in the Baraboo Syncline contains approximately 500 feet of iron-rich banded iron formation, soft hematitic ore, carbonate with quartz, iron silicates, and some clay. The soft hematite ore was mined in underground workings from 1903 to 1925 but mining ceased because of the cost of pumping the large volume of water that flowed into the mine (Clayton and Attig 1990). The Freedom Formation is not exposed at the surface and the only information available is from descriptions of the ore in mine and drilling records published by Weidman (1904), and Schmidt (1951). A large volume of soft ore still remains underground but most of it is overlain by Cambrian rocks and Pleistocene sediment and may not be profitable to mine because of its depth below the Earth's surface (Clayton and Attig 1990).

Black River Falls District

The taconite deposit in the Black River Falls District is a metamorphosed iron formation containing magnetite, quartz, amphiboles, biotite, and garnet. The ore body is a lens 3000 feet long and 500 feet wide that strikes northwest and dips 70-80 degrees southwest. It is bounded on the southwest and northeast by siliceous schist. The rocks are strongly deformed and bedding is isoclinally folded (Jones 1978). This relatively small ore body was mined from 1969 to 1983 by the Jackson County Iron Company (WGNHS 2011).

Florence District and Iron Ranges in Northeastern Wisconsin

The Florence District in northeastern Wisconsin contains iron formation of varied mineralogy that includes abundant magnetite, siderite, and pyrite. The iron formation is only slightly metamorphosed but is very intensely folded (James 1951). Although the amount of iron remaining is large, the complex deformation currently makes it unattractive for mining.

Northwest of the Florence District are four small iron ranges: the Marenisco Range, the Turtle River Range, the Vieux Desert District, and the Conover District (Dutton 1983). The iron deposits in these ranges are relatively small in comparison to those of the Florence and Gogebic-Penokee Ranges.

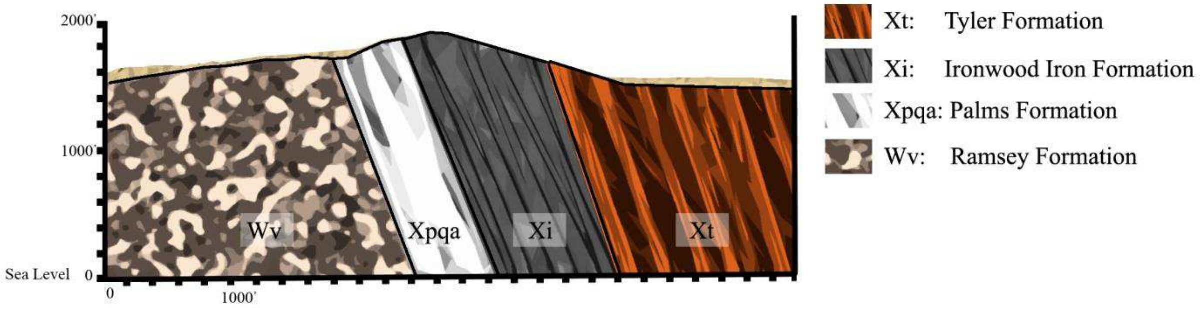


FIGURE 4. GEOLOGIC CROSS SECTION OF THE PENOKEE RANGE NEAR UPSON, WISCONSIN. THE SECTION IS DRAWN TO SCALE WITH NO VERTICAL EXAGERATION (HESTER AND FITZ, 2013).

Penokee-Gogebic District

The Ironwood Formation of the Penokee-Gogebic District is a taconite iron formation that forms the backbone of the Penokee Range from the area of Jackson Lake in Bayfield County east 75 miles to Lake Gogebic in Michigan. The formation forms a ridge commonly referred to as the "Penokee Range" in Wisconsin and the "Gogebic Range" in Michigan. The Ironwood Formation is approximately 600 to 800 feet thick and has been subdivided into five members, from bottom to top these are: Plymouth, Yale, Norrie, Pence, and Anvil. Natural ore was mined in the Penokee-Gogebic Range from 1887 to 1967, primarily from underground workings (Cannon et al 2008). Taconite ore containing 20% to 30% iron by weight occurs in an upper and a lower ore zone which together constitute about 1/2 to 2/3 of the formation. The 21-mile stretch of Ironwood Formation between Mineral Lake in Bayfield County and Upson in Iron County is estimated to contain 3.7 billion tons of taconite ore (Marsden 1978), making it among the largest undeveloped taconite deposits in Lake Superior Region (Cannon et al. 2008).

The Ironwood Formation consists of quartz in the form of chert, iron oxide, and lesser amounts of siderite, chamosite, stilpnomelane, biotite, chlorite, and pyrite (Bjornerud 2012; Huber 1959; Schmidt 1980). Although pyrite is a minor constituent, it is locally abundant. An especially pyrite-rich zone 10 feet thick containing up to 20% pyrite has been documented in the Yale member from drill core extracted just west of Pence in Iron County (Bjornerud et al. 2012). Limited sampling of the Ironwood Formation suggests it has phosphorus (as P_2O_5) concentrations of about 0.15 wt. % (660 mg P/kg rock), similar to those in the overlying Tyler Formation (Bjornerud et al. 2012).

Bedding dips 60-70 degrees north along the Penokee Range in Wisconsin (Figure 4), so mining of the Ironwood Formation to a depth greater than about 400 feet would require the removal of rocks from the underlying Palms and overlying Tyler Formations. Rock from these formations would be broken and exposed to weathering so their mineralogy and geochemistry would influence the chemical and biological processes in waste rock piles and thus the chemistry of leachate from the spoils.

The Palms Formation is 400-500 feet thick and is composed of slate and quartzite containing very little if any pyrite.

The Tyler Formation sits stratigraphically above the Ironwood and is approximately 6800 feet thick in Wisconsin (Schmidt 1980). The lower part of the Tyler is relatively non-resistant to erosion and is very poorly exposed at Earth's surface, thus little is known about the lowermost 600 feet of the formation. Drill cores and the few surface exposures reveal that this section is mostly pyritic black slate composed of quartz, muscovite, chlorite, pyrite, magnetite, sodium feldspar, and siderite (Bjornerud et al. 2012; Cannon et al. 1996). Limited sampling of the Tyler Formation suggests carbonate minerals other than siderite are rare and that phosphate (reported as P_2O_5) could constitute about 0.16 % weight of the rock (700 mg P/kg rock) throughout the formation (Bjornerud 2012). The mineralogy and geochemistry of the rocks in the lower part of the Tyler Formation need to be well understood in order to accurately assess the acid-producing potential of waste rock from an iron mine in the Penokee Range. Surface exposures are too few to characterize the lower Tyler and this section of the stratigraphy would have to be studied in drill cores.

The upper part of the Tyler is more resistant to erosion and is fairly well exposed. It consists of fine quartzite with sand-sized quartz clasts and 1-2% pyrite.

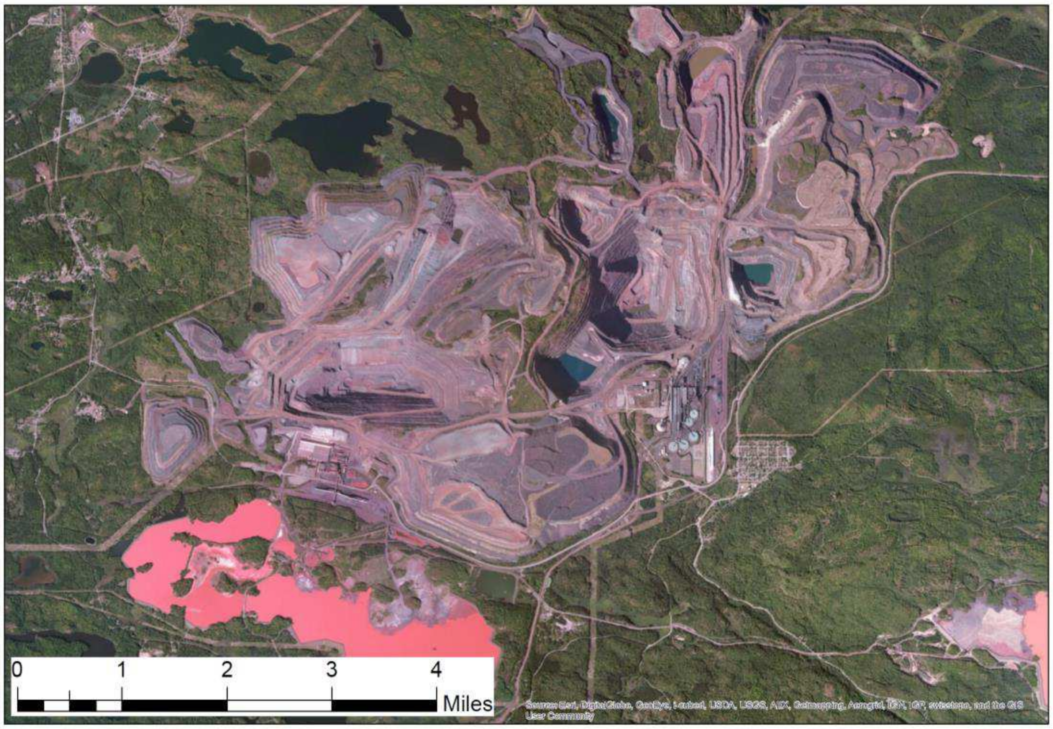
1.3. THE TACONITE MINING PROCESS

The mining and processing of taconite differs considerably from the largely underground, high-grade iron ore mines that defined iron mining in the Lake Superior region prior to the mid-20th century. Taconite operations consist of two major processes, extraction and beneficiation. Extraction consists of drilling and blasting the ore and overburden. Beneficiation is the process of concentrating and pelletizing the ore. Taconite operations typically consist of a mine pit, waste rock and tailings disposal areas, and processing plants and associated facilities.

The first step in extraction is to drill a field of holes approximately 16 inches in diameter and 45 to 55 feet deep (USEPA 2002a), as shown in Figure 5. Spacing between holes is dependent on the properties of the rock being blasted, and is typically 25-35 feet. These holes are filled with a blasting agent (commonly ANFO, a mixture of ammonium nitrate fertilizer and fuel oil), and blasts are timed to sequentially break up the rock in the desired manner. Hazards associated with blasting include “flyrock”, ground vibrations, dust and gas exposure, and particularly “airblast,” which can cause structural damage to nearby buildings (USBOM 1987). Following blasting, large shovels load the crude ore onto trucks for transport to primary crushers. The initial phase of mine development as well as mine pit expansion involves the removal of overburden - non-ore rock overlying the deposit of interest. The ratio of overburden that must be removed to crude ore is known as the “stripping ratio.” The stripping ratio can be as low as 0.5 for taconite mines, and is around 1.0 for mines currently operating in Minnesota (USEPA 1994a; Zanko 2011). Waste rock is typically stored in unlined piles on site.

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

FIGURE 5. DRILLING OPERATIONS IN PREPARATION FOR SURFACE BLASTING AT THE MINNTAC MINE IN MOUNTAIN IRON, MN. THE DRILL RIG IS VISIBLE AT LEFT.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

FIGURE 6. THE EMPIRE AND TILDEN MINE PITS NEAR ISHPEMING, MI.

The processes employed in beneficiation vary from mine to mine, and depend on the properties of the ore being processed. However, major steps include crushing, grinding, thickening, magnetic separation and/or flotation, balling, and induration. Primary crushing typically takes place in the mine pit, and reduces the ore to about 6-10" in diameter. Additional crushing reduces particle size further, to 0.5-0.75" in diameter (USEPA 1994a; 2002). As of 2002, mining operations in Minnesota and Michigan employed between one and four stages of crushing (USEPA 2002a; 1997a). The crushed ore is then subjected to several stages of grinding. Between each stage of the crushing and grinding process, ore is screened and undersized or oversized ore is routed to the appropriate stage. The finished product is a fine powder, with a particle size of about 0.44 microns. (USEPA 1994a).

For magnetic taconite ores (magnetite), the next major step is magnetic separation. During this process, ore, usually in slurry, is moved through a series of separators that work on progressively smaller particles. A rotating cylinder containing a magnetic field in its lower portion passes through the ore slurry. Magnetic particles adhere to the cylinder until it rotates past the end of the magnetic field, at which point they are collected by a weir (USEPA 2002a).Tailings from magnetic separators may be reground and reprocessed or discharged.

Flotation is a process which utilizes chemical reagents to encourage either the iron-bearing ore or the gangue (the valueless minerals, predominately silica in most taconite ores) to preferentially bind to air bubbles, while the other is removed. Modern taconite operations typically use cationic flotation, meaning that the gangue (i.e., waste material) is floated while the valuable minerals settle (USEPA 1994a). Chemicals used in the flotation process are organic compounds and mixtures formulated for three main purposes – to stabilize air bubbles, to bind solid particles to air bubbles, and to encourage particle settling. These reagents adhere to particles, and thus typically end up in the tailings disposal facility (USEPA 1994a).

In 1990, 42% of iron ore produced in the U.S. was treated with magnetic separation alone, 51% of ore produced was treated with magnetic separation followed by flotation in order to upgrade the ore, while 6% of ore was treated with flotation alone (1% was produced using gravity concentration) (USEPA 1994a). The process design at a given facility is a function of the magnetic properties of the ore at that location. While the majority of taconite mines in the Lake Superior region are mining primarily magnetite ore, there are large reserves of nonmagnetic ores (e.g., hematite) present in the area as well. The Groveland mine on the Menominee range in Michigan used flotation to process a hematite/magnetite ore (Heising 1963). From the 1960s through the 1980s, research was carried out by the former Bureau of Mines on beneficiation methods for nonmagnetic ores from the Marquette range in Michigan and western Mesabi range in Minnesota (e.g., Frommer and Wasson 1962; Drost and Mahan 1973; Frommer et al. 1973; Colombo et al. 1978). The Tilden mine on the Marquette range opened in 1974, utilizing a novel flotation process to concentrate hematite ore in addition to magnetite (Colombo and Jacobs 1976), and continues operation today. Essar Steel Minnesota is currently developing a mine on the western end of the Mesabi range in Minnesota where considerable hematite resources (in addition to magnetite) exist. Known reserves in Wisconsin, including the Gogebic deposit, are primarily magnetite taconite. However, considerable quantities of hematite are present in the Butternut deposit (Marsden 1978) and in the Wisconsin portion of the Menominee range (i.e., the Florence district) (Green and Colombo 1984).

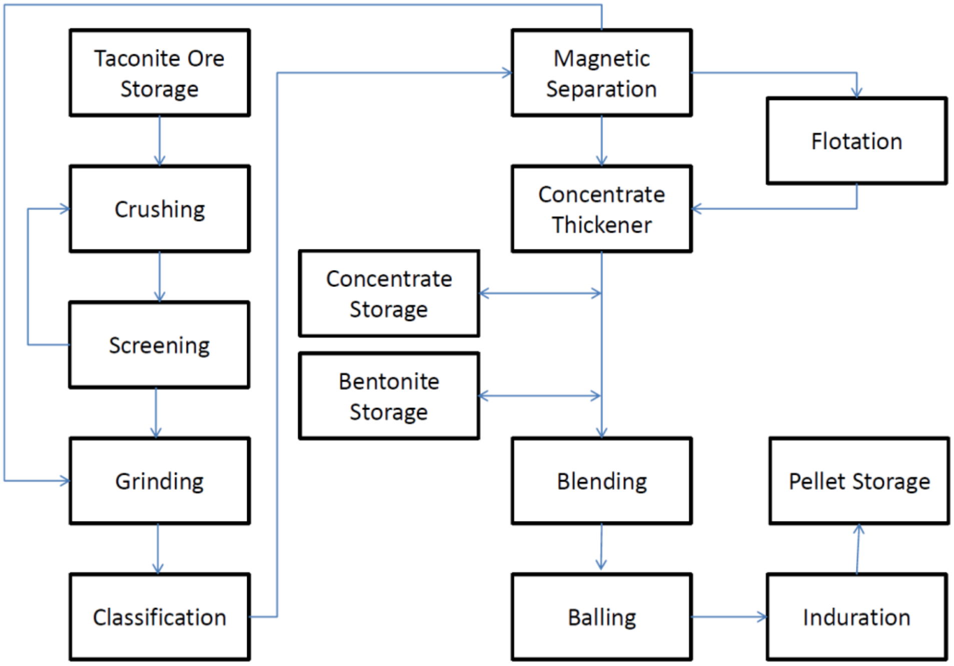
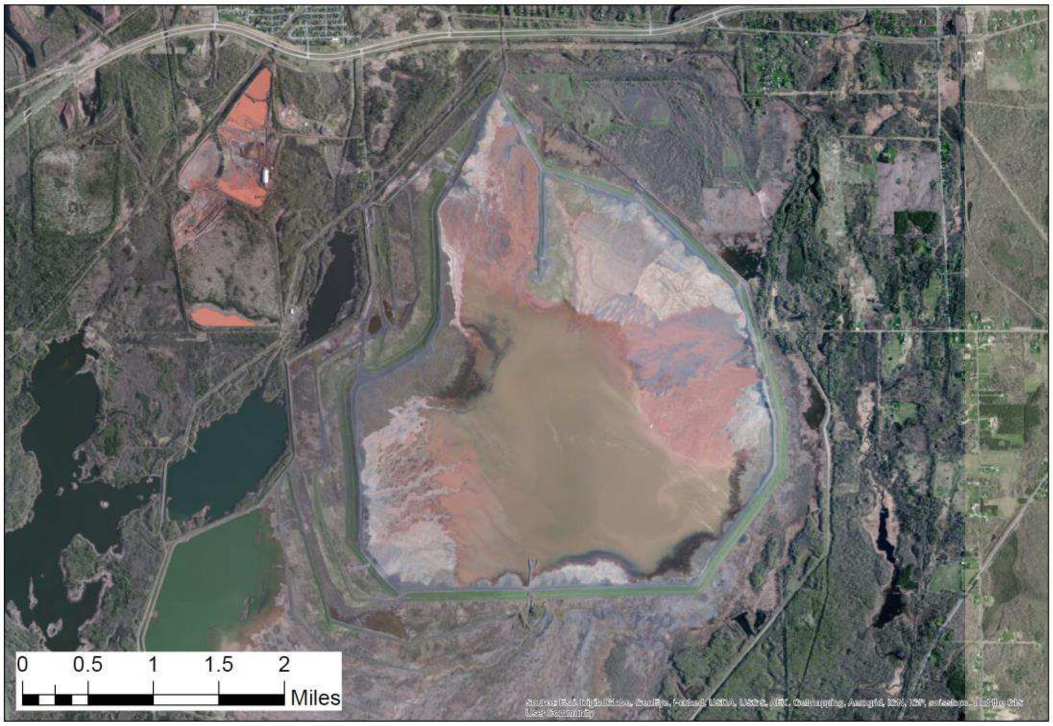


FIGURE 7. SCHEMATIC OF TACONITE MINING PROCESS. CONDENSED FROM FIGURE 11.23-1 IN U.S.EPA 1997.

Following magnetic separation and/or flotation, the ore concentrate is sent to a thickener where excess water is removed, and then moves to the pelletizing process (while a small portion of iron ore is shipped from the Lake Superior region in other forms, most is pelletized). Pellets can be either standard (acid), or fluxed, in which 1-10% limestone or dolomite is added to improve blast furnace recovery and efficiency. Fluxed pellets are described by their basicity, defined as the mass ratio of the sum of calcium oxide and magnesium oxide to the sum of silicon oxide and aluminum oxide in the pellets, with fully fluxed pellets having a basicity of one or greater (USEPA 2002a). The majority of taconite pellets produced today are at least partially fluxed (Tuck and Virta 2013). Regardless of pellet type, a binder (typically bentonite) is also added to the concentrate at 10 to 20 pounds per ton (USEPA 1997a). Balling drums are used to roll "green" pellets, which are then hardened by heating in a kiln or furnace at 2350° to 2550°F (USEPA 1997a).

Taconite mining and processing requires the use and management of a large quantity of water. The mine pit must typically be dewatered below the depth of the groundwater table, and runoff from mining and processing areas must be managed. Beneficiation processes require a large amount of water – ore and tailings are typically transported and treated in slurry throughout most of the process, and additional water is required for emissions control devices. The majority of process water is recycled from thickeners or tailings basins so that often less than 10% comes from outside sources (USEPA 1994a). The Essar Steel facility in Nashwauk, Minnesota, which will include direct-reduced iron and steelmaking facilities in addition to taconite mining and pellet production, will derive all process water from stormwater runoff, mine pit dewatering, and recycling (MPCA 2012).



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

FIGURE 8. TAILINGS BASIN AT KEETAC (KEEWATIN, MN). TAILINGS AND WASTEWATER ARE PUMPED IN A PIPELINE TO THE BASIN FROM THE PLANT. THE TAILINGS ARE CONTAINED BY DIKES, PARTIALLY BUILT WITH COARSE TAILINGS.

Tailings generated during processing are disposed of in ponds or impoundments in currently operating taconite mines. Dams or dikes are constructed to contain the tailings, as shown in Figure 8. The solids settle and water is recycled from the basin. The tailings basin may be lined or unlined, and must be sized to handle waste for the lifetime of the mine. Dry stacking is an alternate tailings disposal technique under discussion for projects that have been proposed in Wisconsin (Olivio 2013). In this method, tailings are dewatered using vacuum filtration, then transported to a storage area and compacted in a “dry stack”. While more expensive than conventional tailings disposal, this method has the advantages of requiring a smaller footprint and a reduced potential for contamination of water resources (Davies and Rice 2004; Davies 2011).

The final step in a taconite mining project is reclamation. Land areas (e.g., tailings disposal basins) can be covered and revegetated (e.g., Applied Ecological Services 2008). Areas of the mine pit can be refilled with waste rock, or, following the cessation of dewatering, it can be left to fill with water, forming an artificial lake. The former Jackson County iron mine (Figure 2) is the only example of a reclaimed open-pit taconite mine in Wisconsin.

2. ENVIRONMENTAL AND ECOLOGICAL CONSIDERATIONS

Because a large taconite deposit located in the Gogebic District of Ashland and Iron counties (Section 1) is currently being evaluated for a mine, this section of the report is written to be particularly relevant to water, land, and air resources within that region of the state. Six watersheds with a total surface area of ~1300 square miles transect the Gogebic Range in Wisconsin and drain to Lake Superior (Table 1; Figure 9). Collectively these watersheds contain ~600 lakes and 200 streams spanning ~1000 miles. Sixty-six of the water bodies are classified as Outstanding Resource Waters (ORW) or Exceptional Resource Waters (ERW). Many of the streams support excellent trout fisheries. The watersheds are heavily forested with northern hardwoods and mixed conifers, and wetlands are abundant.

TABLE 1. WATER RESOURCES WITHIN THE GOGEBIC DISTRICT OF NORTHERN WISCONSIN

Watershed	DNR Code	Area miles^2	Lakes No.	Lakes acres	Streams No.	Streams miles	ORW/ERW No.
Lower Bad River	LS09	123.9	40	416	11	101	3
White River	LS10	366.2	328	7166	45	224	16
Potato River	LS11	139.9	16	154	25	113	7
Marengo River	LS12	217.5	77	1405	41	151	20
Tyler Forks	LS13	78.8	22	151	21	84	6
Upper Bad River	LS14	134.7	39	1081	29	129	7
Montreal River	LS15	226	73	1332	40	165	7
Total		1287	585	11705	212	967	66

(Source: http://dnr.wi.gov/water/watershedSearch.aspx)

The Penokee-Gogebic Iron Range (PGIR) is a geologic feature that dominates the Gogebic District. It is a long, narrow ridge the crest of which rises 100 to 400 meters above the broad river valley sloping north toward Lake Superior. In some places the range is gently rounded, in others it is narrow, steep-sided and serrated. The highest point on the crest of the range is Mt. Whittlesey, the third-highest point in Wisconsin (elevation 571 meters above sea level (masl)). A portion of the range is broken by gaps where several streams flow northward to Lake Superior (elevation 181 masl). Most streams are of moderate size, often with waterfalls and rapids in the narrow gorges where they cross the resistant rocks of the Range.

A comprehensive assessment and management plan should include all elements of the water budget (storage, surface runoff, groundwater flow, precipitation, evaporation, diversion and consumption) as well as important water quality variables in potentially impacted watersheds (e.g., pH, ANC (acid neutralizing capacity), conductivity, temperature, dissolved oxygen, turbidity, Al, Ca, Mg, S, C, Na, Cl, Mn, Se, Fe, Zn, Cd, Cr, Cu, Pb, Hg, N, P). Open-pit mining alters the hydrology and geochemistry of adjacent watersheds. The degree of alteration depends on the scale of perturbation and the efficacy of preventive measures implemented.

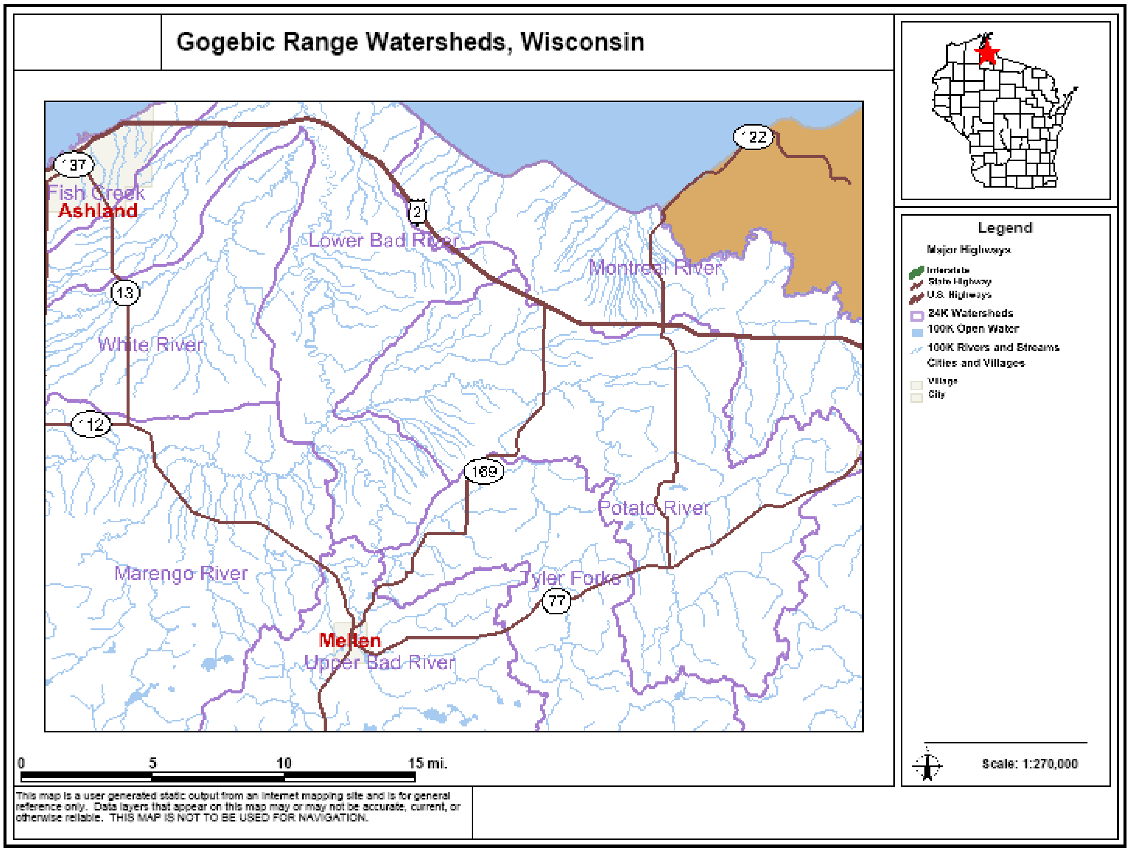


FIGURE 9. MAJOR WATERSHEDS ADJACENT TO THE PENOKEE-GOGEBIC IRON RANGE (PGIR) IN NORTHERN WISCONSIN. LAKE SUPERIOR AT TOP OF MAP.

2.1. HYDROLOGY

Open-pit taconite mining has the potential to alter the flows and storage of surface waters and groundwaters. For example, given the elongated nature of the iron deposits that extend through parts of the adjacent watersheds in the Gogebic Range, a large mining pit could span multiple watersheds transporting water from one to another (Adams 1994). An elongated mine pit could receive groundwater input as simultaneous seepage from two or more watersheds, while dewatering of the pit might create discharge to only one. Leaving "saddles" of land in mine pits situated along watershed divides has been proposed to separate flows (Herr and Gleason 2007).

Taconite mine development proceeds in a series of steps that can sequentially affect different elements of the hydrologic budget (Figure 10). The first step would likely involve removal of trees and other vegetation from the future pit site, processing sites, access roads and service areas. As a result, rates of evapotranspiration would be expected to decline, and water yield would be expected to increase (cf. Hornbeck et al. 1993). Owing to the relatively steep topography and shallow regolith overlying low permeability bedrock in the PGIR, groundwater recharge prior to disturbance is probably low – as evidenced by the abundance of wetlands and small streams draining the area. After the forest cover is removed, surface runoff and the erosional transport of disturbed soils will increase, especially during storm events.

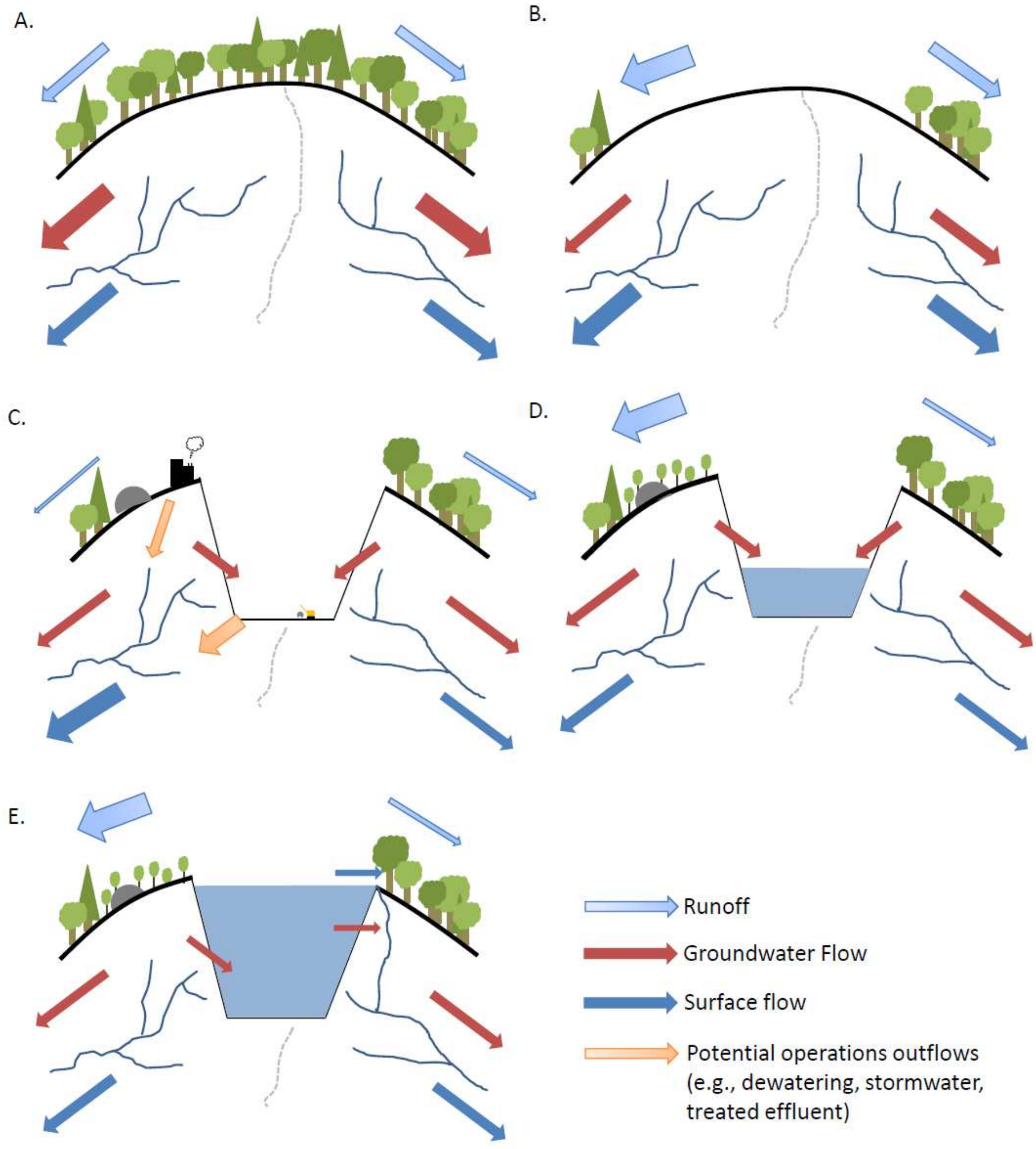


FIGURE 10. SIMPLIFIED DIAGRAM OF POTENTIAL HYDROLOGIC ALTERATIONS ASSOCIATED WITH THE VARIOUS STAGES OF A TACONITE MINING OPERATION. A: MANY MINE SITES ARE LOCATED IN FORESTED HEADWATER AREAS AND SPAN TWO OR MORE WATERSHEDS. B: INITIAL AND ONGOING VEGETATION REMOVAL CAN LEAD TO TEMPORARILY INCREASED RUNOFF AND DECREASED INFILTRATION. C: ONCE THE MINE PIT BEGINS TO DEVELOP, IT BECOMES A HYDROLOGIC SINK, RECEIVING GROUNDWATER INFLOW AND DIRECT PRECIPITATION. SOME OR ALL OF THE WASTE WATER (E.G., PIT DEWATERING FLOW) ASSOCIATED WITH THE MINE MAY BE DISCHARGED TO SURFACE WATERWAYS, POTENTIALLY INCREASING DOWNSTREAM FLOW. D: ONCE MINING CEASES, THE PIT MAY BE ALLOWED TO FILL WITH WATER. RUNOFF FROM RECLAIMED SURFACE AREAS IS ALTERED FROM PRE-MINING CONDITIONS, AND THE LOSS OF OPERATIONS OUTFLOWS MAY ALTER SURFACE HYDROLOGY IN THE WATERSHEDS TO WHICH THEY WERE DISCHARGED. E: AS THE PIT FILLS, GROUNDWATER INFLOW WILL DECREASE UNTIL THE WATER ELEVATION REACHES THE DOWNGRADIENT GROUNDWATER ELEVATION, AT WHICH TIME GROUNDWATER OUTFLOW WILL COMMENCE. DEPENDING ON THE TOPOGRAPHY AND HYDROLOGY OF THE SITE, SURFACE OUTFLOW FROM THE PIT MAY EVENTUALLY OCCUR AS WELL, INCREASING DOWNSTREAM FLOWS.

During active mining operations, the mine pit functions as a hydrologic sink receiving groundwater inflow and storm water. Due to the relatively low transmissivity of the bedrock that characterize much of the PGIR, subsurface flow into the mine workings is expected to occur largely via fractures (Stuart et al. 1954; Adams 1994). Groundwater and direct precipitation inputs to the pit must be pumped out (mine dewatering), often at a rate of several thousand gallons per minute (Adams 1994). Dewatering can create a large cone of depression, lowering groundwater elevations around the pit (Stuart et al. 1954). Operations can utilize some or all of the pit water in beneficiation and pellet manufacturing, or it may be discharged to surface waters. In the latter case, some or all the surface runoff and infiltration that is "lost" to the pit footprint is replaced by this flow. Additional surface discharges (e.g., stormwater, treated wastewater) may exist as well.

Following the end of active mining operations, the mine pit may be left to fill with water, creating an artificial lake (e.g., Lake Wazee, Figure 2). If mine water was being discharged to surface features during operation, the cessation of dewatering can produce a shift in downstream flows and/or water levels. The time required for the pit to fill completely with water is dependent on pit size and the specific hydrology of the site, but abandoned pits in Minnesota have been predicted to require between 5 and 20 years to reach capacity (Adams 1994; Adams et al. 2004). As the pit fills, the difference in elevation between the newly forming lake and the surrounding water table decreases, resulting in decreased groundwater inflow. As the lake level continues to rise to the elevation of the down-gradient water table, groundwater outflow will commence. Finally, depending on the water balance and topography of the pit, lake elevations may continue to rise until surface outflow occurs. It should be noted that the lowest pit rim elevation may not be located where outflow is desirable, and channels should be installed as part of the reclamation process to guide outflows, if necessary (Adams 1994). Pit lakes can have a high surface area to watershed area ratio which can buffer storm flows (Herr and Gleason 2007). Peak flows downstream from pit lakes may, therefore, be reduced relative to pre-mining conditions.

In-pit tailings disposal has been proposed for some mines (e.g. Minorca pit near Virginia, MN), and this practice may produce additional hydrologic effects (Adams 1998). The groundwater interactions of a pit filling with tailings slurry are in some ways analogous to those of a pit filling with water. However, the slurry itself represents an additional input and water removal from the tailings pond constitutes an additional output. As the tailings are stacked above the pit rim, a mounded water table can form (Adams 1998). Groundwater flow through the tailings may negatively affect downgradient water quality (as described below)

Land reclamation following closure of the mine or mine sections can have long-term effects on hydrology. At abandonment, dikes surrounding tailings ponds may be breached so the impoundment will no longer hold water. In a study of such a site, Myette (1991) found that infiltration rates on the former tailings basin were very high, and that runoff only occurred after heavy rains and snowmelt. In addition, the study found that heavy metals in wells surrounding the site and at the outflow were elevated, and fluoride, manganese and nitrate-nitrite exceeded drinking water standards. Groundwater flowed radially away from a mounded water table in the former basin. This site had been only temporarily vegetated, as it was planned to be used as an area to deposit additional tailings as the neighboring basins grew in size. In a study of large-scale reclamation following surface coal mining (replacing overburden and topsoil and revegetating), on the other hand, Ferrari et al. (2009) documented a significantly increased runoff to infiltration ratio, resulting in an increased flood risk. The specific long-term hydrologic alterations attributable to mine reclamation at the surface, therefore, are specific to the site and practices employed.

HYDROLOGICAL MONITORING AND MODELING

To quantify any alterations to surface and groundwater resources, hydrology would ideally be thoroughly characterized prior to any large-scale mining operations. Because of the natural variability in water storage and flow due to fluctuations in precipitation and evapotranspiration, long-term data should be used to characterize baseline conditions where available. Because sufficiently long-term data are not likely to always be available, nearby “reference” watersheds may also be monitored in order to separate regional hydrologic variability from the direct effects of mining. Continuous stream flow monitoring should be conducted in watersheds likely to be directly affected by mining activity prior to, during and following mine development. Precipitation amounts, groundwater levels and surface water levels should also be monitored continuously. Based on these data, the large-scale hydrologic impacts of mining may be explored using numerical models such as MODFLOW (McDonald and Harbaugh 1988). Streamflow hydrograph analysis can be used to determine current groundwater recharge rates. Monitoring wells can be established to characterize groundwater levels, surficial geology, and the hydraulic properties of the soil and bedrock. Horizontal variability in conductivity can be present (Jones 2002). Fractured bedrock, common in iron formations, presents an additional challenge to model accuracy.

Following mining operations, if a pit lake is to be formed, data should be collected during filling (Adams 1994). A site-specific regression for net groundwater flow as a function of water elevation can be developed, and using this information and local precipitation data, it can be accurately determined whether or not an outflow channel should eventually be constructed (and if so, be properly sized).

2.2. POTENTIAL POLLUTANTS

This section describes pollutants of concern when considering the environmental and ecological impact of a taconite mining operation. This is not meant to be an exhaustive list of potential pollutants from such an operation, but rather focuses on those that are of particular concern considering the unique nature of open-pit taconite mining and the locations in Wisconsin in which it is likely to occur.

The impacts of taconite mining on water quality in this region depend largely on the rate at which solutes of concern are mobilized from piles of waste rock, tailings and pit surfaces as a result of exposure to air and water. Spillage of process chemicals, fuel and other service-related materials is generally considered of secondary importance due to the large volume of solid rock waste generated during the mining process. Industry-wide, it is estimated that ~90% of the geologic material handled during metallic mining constitutes waste material, posing a disposal challenge (Jamieson et al. 2011). When waste rock surfaces are exposed to air and water, geochemical weathering solubilizes and mobilizes elements and compounds that can affect ecosystem and human health.

ACID MINE DRAINAGE (AMD)

Acid mine drainage (AMD) is a phenomenon commonly associated with mining of deposits that contain metal sulfide minerals (e.g., Nordstrom 2011). Pyrite and other sulfide minerals are stable under reducing conditions deep underground but are unstable and undergo relatively rapid chemical weathering when exposed to oxygen, water, and microorganisms near the Earth's surface (Edwards et al. 2000). Through several reaction steps, pyrite reacts with oxygen and water to create sulfate ions and ferric iron ions, releasing protons in the process (e.g. Langmuir 1997). A commonly written reaction pathway is the oxidation of pyrite (FeS_2), a non-magnetic iron mineral that co-occurs with magnetic forms such as magnetite (the iron oxide of primary interest in taconite mining):

$$FeS_2 + {}^{15}/_{4}O_2 + {}^{7}/_{2}H_20 \rightarrow Fe(OH)_{3(s)} + 2H_2SO_4 \qquad (1)$$

Equation 1 oversimplifies the processes that can occur can under environmental conditions, but it illustrates how strong acid (H_2SO_4) can be generated as a byproduct of mining activity in the presence of metal sulfides. The reaction shown in equation 1 slows down at very low pH, but the proliferation of iron-oxidizing micro-organisms can speed it up again. These micro-organisms can satisfy their carbon needs from CO_2 in air and their energy needs from the oxidation of inorganic substrates such as F^{2+} and sulfur (Nordstrom 2011). The oxidative dissolution of pyrite takes places faster in fine-grained materials (Nordstrom 2012; U.S. Environmental Protection Agency 1994b), so the grain size of broken rock in mine waste rock and tailings disposal facilities influences the rate at which the dissolution reactions take place. Ferric iron (Equation 1) is precipitated as iron hydroxide at pH above 3, whereas the sulfate ions can remain in solution, and the protons decrease the pH of the solution. The low pH of the solution mobilizes many metal ions released during weathering. Since AMD is a complex phenomenon that involves geochemical and biological processes, it can be challenging to predict rates of acid formation.

TABLE 2. SULFIDE MINERALS DETECTED IN MORE THAN ONE SAMPLE FROM THE TYLER FORMATION IN PGIR (SOURCE: BJORNERUD ET AL. 2012)

Mineral name	Formula	Number of samples (out of 18) in which found
Pyrite/Marcasite	FeS_2	7
Pyrrhotite	FeS	6
Mackinawite	FeS	5
Greigite	Fe_3S_4	4
Other iron sulfide	Fe_3S; Fe_9S_{11}	3
Troilite	2HFeS	4
Metacinnabar	$HgSe_{0.6}S_{0.4}$	2

The potential for acid generation in the PGIR and its consequences depend on a number of factors. The presence of pyrite in some iron formations and adjacent units in Wisconsin means that weathering of waste rock could affect the pH of surface and groundwater. Given the mass and sulfide content of disturbed rock, one can roughly estimate an upper limit for the acid generating potential of mine waste.

An empirical approach for estimating the acid generating potential of mine sites involves the use of humidity cells at the bench-top scale. The cells are filled with crushed rock and subjected to a wetting-drying schedule that mimics hydrologic conditions at the site. Output water from the cells is analyzed for pH, conductivity and solute content and then the results are scaled up to the proposed mine dimensions (see Section 6.2).

To assess the acid mine drainage potential of future mine sites in the PGIR, it is recommended that both numerical and empirical approaches be used. Robust and proven best management practices (BMPs) should be in place to minimize AMD prior to mining if it is determined that AMD could be a problem.

ALUMINUM

The disappearance of fish from northern lakes was a consequence of acid rain in North America and Europe during the 1960s and 1970s (Likens et al. 1979), and laboratory experiments identified aluminum-mediated gill necroses as a causal mechanism underlying fish mortality in watersheds receiving acidic atmospheric deposition (e.g. Leino and McCormick 1992; McCormick and Jensen 1992). Aluminum mobilization would be expected as a consequence of AMD. For example, Gibbsite ($Al(OH)_3$), a common mineral form of Al with low solubility (K_{sp} ~3×10^{-34}), can react with sulfuric acid to form readily soluble aluminum sulfate (alum) according to:

$$2Al(OH)_3 + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 \cdot 6H_2O \qquad (2)$$

Since Al is an abundant element in the Ironwood and Tyler formations (Bjornerud et al. 2012), the potential for Al mobilization and the toxicological consequences for fisheries in the PGIR should be fully assessed. If necessary, mitigation strategies should be developed and implemented prior to mining in the PGIR region.

SULFATE

In addition to being the strong acid anion of concern for AMD, sulfate mobilization from mining waste has other potential consequences in the PGIR. Consequences of concern include potential impacts on wild rice and the stimulation of mercury methylation by sulfate reducing bacteria (discussed further below).

The background concentration of sulfate in surface waters of northern Wisconsin typically ranges from about 1 to 3 mg/L, consistent with the average sulfate concentration in regional precipitation (~1 mg/L). This background concentration is similar to that reported for non-mine impacted streams in the headwaters of the St Louis River system (SLR) in northwestern Minnesota, a region with intensive taconite mining activity (Berndt and Bavin 2012a). In contrast, sulfate concentrations in streams down gradient from mine waste can be two orders of magnitude higher in the SLR watershed, reflecting the oxidation and mobilization of minor sulfide minerals from the Biwabik Iron Formation (Berndt and Bavin 2009; 2012a; Figure 11).

Interestingly, sulfate export from mine waste in the SLR region is not associated with AMD due to neutralization by the dissolution of carbonate minerals that are abundant in the Biwabik formation. Instead, the mine-impacted waters tend to have high bicarbonate alkalinity and hardness (Mg^{2+} and Ca^{2+}) compared to SLR catchments not connected hydrologically to mines (Berndt and Bavin 2012b). Berndt and Bavin estimated that the export of sulfate from mine waste to the SLR averaged 35 metric tons per day.

Hanna and Lapakko (2012) conducted a site-intensive investigation of sulfate export from waste rock at a former taconite mine at the eastern end of the Biwabik Iron Formation in MN using a combination of field and laboratory methods. The laboratory method involved humidity cells; and field methods involved the quantification of waste rock mass, sulfide content and sulfate release for a specified period. Estimated rates of sulfate export agreed reasonably well between methods, ranging from 8 to 28 g SO_4 per kg FeS_2 per year in the field and 22 g SO_4 per kg FeS_2 per year in the lab. In total, Hanna and Lapakko estimated a sulfate release rate of ~9000 tonnes per year from this site.

Given the findings and magnitude of sulfate release rates in the nearby Biwabik Iron Formation, it would be prudent to conduct site-specific investigations of sulfate release prior to mining in the PGIR. Samples from representative cores and engineering estimates of waste rock generation should be considered.

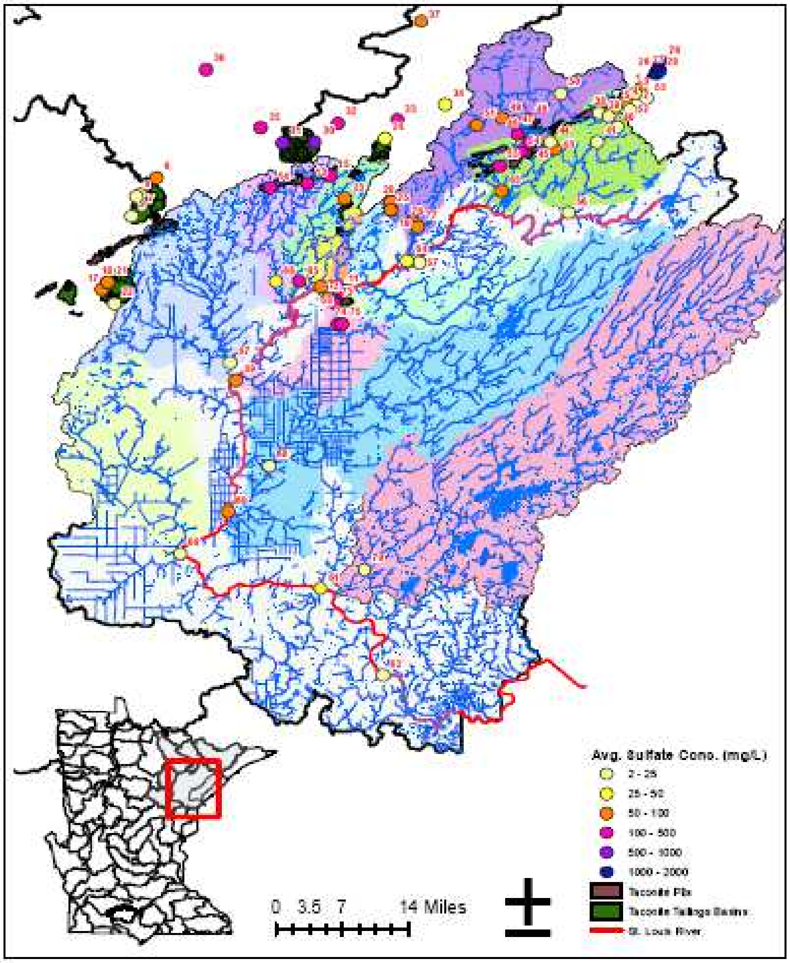


FIGURE 11. AVERAGE CONCENTRATIONS OF SULFATE IN THE ST. LOUIS RIVER WATERSHED OF NORTHWESTERN MINNESOTA (FROM BAVIN AND BERNDT, 2008)

MERCURY AND METHYLMERCURY

Mercury emissions and deposition

Mercury is a component of gas emissions from the heat curing of taconite pellets (Galbreath 2005). Studies at taconite processing facilities in Minnesota have shown that mercury is released from magnetite during the production of taconite pellets (Berndt and Engesser 2005). Recent emission inventories indicate that taconite mining and processing are the largest source of airborne mercury within the Lake Superior basin (Figure 12), and most of the taconite-related Hg emissions are associated with mining activity in northeastern Minnesota. The Minnesota Pollution Control Agency (MPCA) estimates that nine taconite facilities in this region emit a combined total of roughly 257 kg of Hg annually into the Lake Superior airshed as a result of taconite processing (Table 3). This represents 20% of total mercury emitted statewide (Berndt 2003), and current efforts in Minnesota seek to substantially reduce taconite-related mercury emissions (*e.g.,* Benner 2008; Benson et al. 2012a; 2012b, Berndt 2008; Schlager et al. 2012). For comparison, Wisconsin Hg emissions from the four counties within the Lake Superior basin (Ashland, Bayfield, Iron, Vilas) totaled ~18 kg for 2012 (WDNR Air Management Hg Inventory data).).

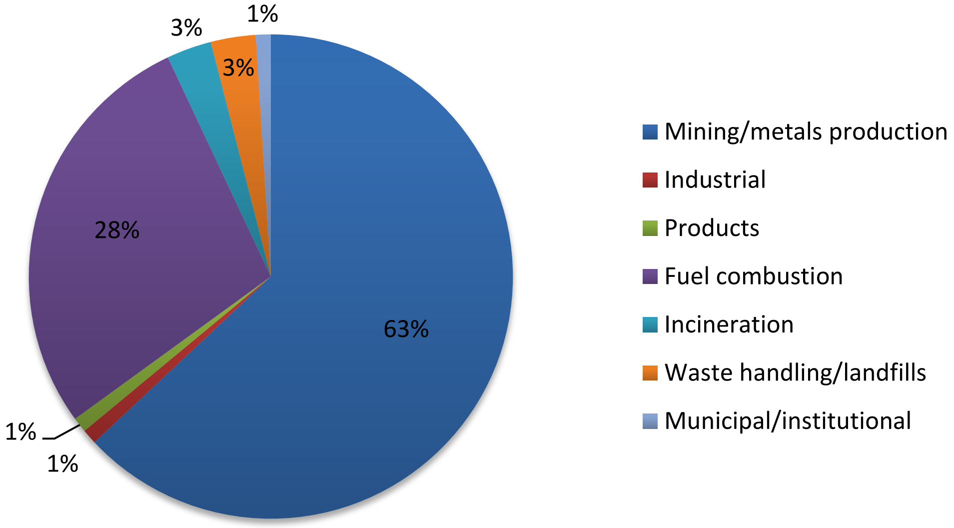


FIGURE 12. PERCENTAGE OF MERCURY RELEASES FROM DIFFERENT SECTORS IN THE LAKE SUPERIOR BASIN. SOURCE: LAKE SUPERIOR BINATIONAL PROGRAM 2012.

According to Berndt (2003), stack emissions are the dominant pathway for mercury release via taconite processing on the iron range of Minnesota. Solid phase Hg(II) in ore concentrate is converted to gaseous Hg(0) during the firing of pellets and released to the atmosphere in stack emissions. An important parameter for estimating emissions from taconite companies is the "emission factor", which represents the mass of mercury released divided by the mass of pellets produced. One of the more common units for expressing emission factors is kg mercury per million long tons of pellets produced (kg/10^6 LT). In northeastern Minnesota, emission factors reflect the primary distribution of mercury in the ore body, and they generally increase in a westward direction across the district from 1 to 17 kg Hg per million long tons of pellets.

TABLE 3. ANNUAL MERCURY EMISSIONS ATTRIBUTABLE TO TACONITE PROCESSING IN NINE FACILITES IN NORTHEASTERN MINNESOTA (SOURCE: MPCA 2010 INVENTORY CALCULATIONS)

Source	Location	Hg emissions (kg/year)			
		1990	2000	2005	2010
Hibbing Taconite	Hibbing, MN	102.6	102.1	103	72.1
US Steel Minn Ore	Mountain Iron, MN	67.6	77.8	84	67.9
United Taconite	Forbes, MN	50.5	48	60.6	57.8
US Steel Corp	Keewatin, MN	48.4	54.8	66.6	35.5
Arceolor Mittel Minorca	Virginia, MN	12.2	15.5	15.2	14.9
Mesabi Nugget	Hoyte Lakes, MN	0	0	0	6.4
Northshore Mining	Silver Bay, MN	1.2	2.1	3.3	2.3
LTU Steel	Hoyte Lakes, MN	39.8	37.7	0	0
Northshore Mining	Babbit, MN	NA	NA	0.05	NA

The fate of Hg emissions within the Lake Superior basin is uncertain. Early measurements of atmospheric Hg0 in remote regions were low and relatively uniform across the northern hemisphere (Fitzgerald, 1989). These observations implied complete hemispheric mixing and, consequently, an atmospheric residence time of about 1 year. Under these conditions, Hg emissions within the Lake Superior basin would be expected to have little local consequence. However, more recent observations across finer spatial and temporal scales suggest that the atmospheric Hg cycle is more dynamic than older global budgets would imply. These new observations imply a short residence time for Hg in the lower atmosphere and intense recycling (Watras et al., 2009 and references therein). Under a short residence time scenario, Hg0 emissions would have substantial local significance. This scenario is consistent with reports of declining atmospheric Hg deposition in the Lake Superior region following the closure of a large smelting facility in White Pine, MI and a regional reduction in the industrial and commercial use of Hg (Engstrom and Swain, 1997; Hrabik and Watras, 2002). Decreases in mercury methylation and bioaccumulation have accompanied the regional decline in Hg emissions and deposition, an observation which implies the potential importance of newly deposited Hg as a source of contamination in aquatic foodwebs (Hrabik and Watras, 2002; Watras and Morison, 2008; Meyer et al., 2011).

As of 2005, there had been a 71% reduction in mercury releases to the atmosphere basin-wide (Lake Superior LaMP [Lakewide Management Plan] 2005). The Lake Superior LaMP 2008 report calls for continued reductions in mercury emissions; and it calls for estimates of new mercury that would be released if mining projects are proposed in Wisconsin or Michigan. The LaMP reports are compiled by the Lake Superior Binational Program, which comprises 25 Federal and State agencies in the US and Canada including the Wisconsin Department of Natural Resources.

Mercury in the environment

Mercury contamination of fisheries in northern WI is well documented, and a region-wide public health advisory cautions people about the consumption of native fish (Section 3.3). There are similar concerns about the effects of mercury contamination on loons and other piscivorous wildlife in the region (Evers et al., 2011). Mercury is one of the few toxic elements (along with selenium, discussed below) known to biomagnify in aquatic foodwebs. Analyses of pelagic organisms from both remote and contaminated lakes indicate that methylmercury (meHg), rather than inorganic mercury ($Hg^{(II)}$), is preferentially transported up the food chain. In sediments, in water, and at the base of the aquatic food chain, meHg constitutes a small but increasing fraction of the total mercury (Hg_T) pool. However, at high trophic levels, almost all of the Hg_T is in the methylated form (Watras, 2009). Methylmercury is a highly toxic form of mercury.

As described above, the dominant source of inorganic mercury to the waters of northern Wisconsin is ultimately atmospheric deposition, whether delivered directly to the water surface or indirectly via watershed runoff. Mercury emitted to the atmosphere by natural processes and by the combustion of fossil fuels is transported atmospherically in the gas phase and subsequently washed out of the atmosphere during precipitation events. Mass balance studies in the region (Watras et al., 1996) indicate that forested terrestrial catchments retain a large fraction of the atmospherically deposited mercury (90 to 95%) due to sequestration by organic matter (Grigal, 2002).

In contrast to inorganic mercury, the dominant source of methylmercury is internal production in anoxic waters, sediments and riparian wetland. The conversion of atmospherically deposited Hg^{II} to meHg is mediated by certain bacteria that inhabit these anaerobic zones. As a result, environmental factors that stimulate the activity of methylating bacteria can exacerbate food chain contamination. Sulfate reducing bacteria (SRB) are considered to be the principal methylators of mercury in aquatic systems (Gilmour et al. 1992; Johnson and Beck 2012). These bacteria utilize sulfate as a terminal electron acceptor in their energy metabolism (rather than oxygen). Field experiments have demonstrated that sulfate additions to northern WI lakes (in the form of simulated acid rain, H_2SO_4) can stimulate SRB activity, enhance the production of meHg and increase levels of fish contamination (Hrabik and Watras 2002; Watras et al. 2006). A diagrammatic summary of the pathways for mercury loading, sulfate loading, mercury methylation and fish contamination is shown in Figure 13.

TABLE 4. HG CONCENTRATIONS (NG G-1) ASSOCIATED WITH TACONITE MINING OPERATIONS IN MINNESOTA (SOURCE: BERNDT, 2003)

Company	Raw ore (ng/g)	Concentrate (ng/g)	Tailings (ng/g)
NSPC	21	15.2	20.4
HibTac	24	16.6	26.0
Minntac	32	8.2	39.5
EVTAC	32	11.4	40.2
IIMC	27	7.8	35.4
LTVSMC	11	4.0	12.2
Northshore	0.6	1.1	1.1

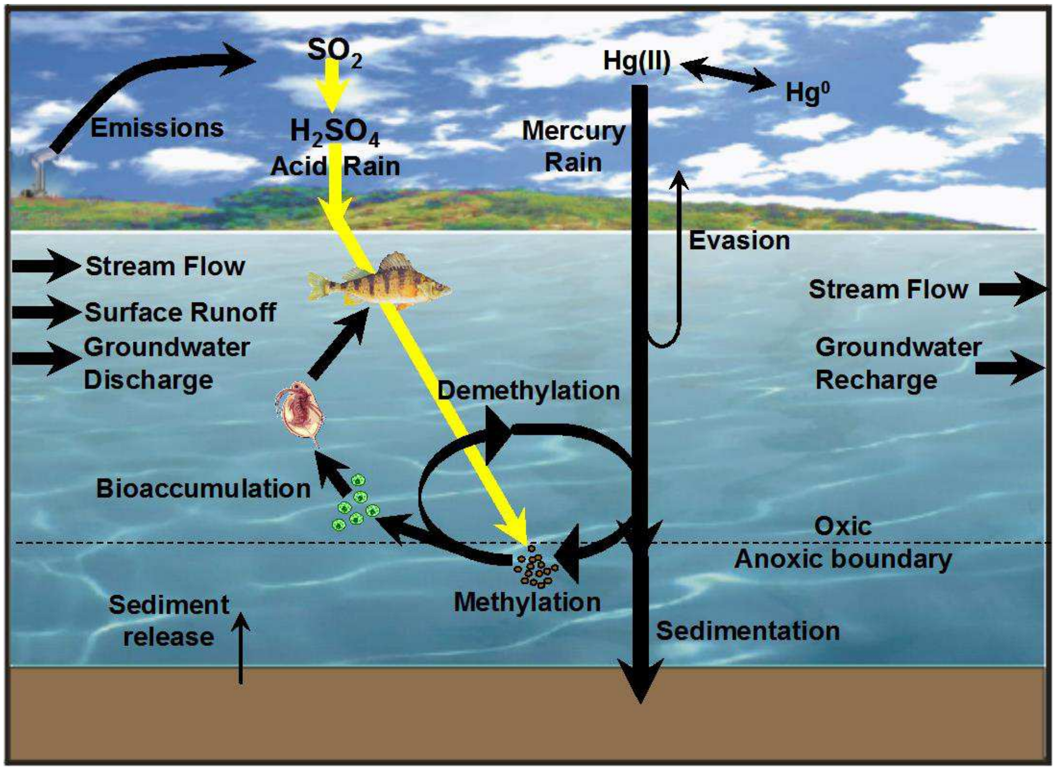


FIGURE 13. THE AQUATIC MERCURY CYCLE IN A REPRESENTATIVE WISCONSIN LAKE (FROM WATRAS, 2009)

With respect to the PGIR, the potential enrichment of surface waters with inorganic Hg and sulfate from mine waste may be exacerbated by the analogous stimulation of the methylmercury cycle in receiving waters. Since metacinnabar is known to be present in the PGIR rock (Table 2), some Hg release from mine waste is possible. However, elevated concentrations of Hg may also be found in organic forest soils and vegetation that will be removed as overburden. Particulate mercury in the forest floor and mineral soil horizons across northern Minnesota and Wisconsin vary over fairly narrow ranges, from about 100 to 250 ng g^{-1} and 15 to 30 ng g^{-1}, respectively (Nater and Grigal 1992). Hg concentrations in living vegetation (tree leaves and stems) tend to be intermediate between forest floor and mineral soil material (Grigal 2002). Hg concentrations in the materials associated with taconite mining operations in Minnesota tend to fall in the range for mineral soils (Table 4). Given the large mass of material that is disturbed during mining activity, these solid sources collectively contain a large store of inorganic Hg. The question of critical importance is whether they will be a source or sink for mercury when exposed to precipitation or other water sources.

The interaction of $Hg^{(II)}$ and SO_4 on methylation rates in anoxic waters and sediments can be described by the equation

$$\mathrm{MMR} = \mathrm{MMR}_{\max} \bullet \left(\frac{\left[\mathrm{Hg}^{(\mathrm{II})}\right]}{k_{\mathrm{Hg}^{(\mathrm{II})}} + \left[\mathrm{Hg}^{(\mathrm{II})}\right]} \right) \bullet \left(\frac{\left[\mathrm{SO_4}^{2-}\right]}{k_{\mathrm{SO_4}} + \left[\mathrm{SO_4}^{2-}\right]} \right) \quad (3)$$

where MMR is the observed mercury methylation rate, MMR_{max} is the maximum rate possible for a given microbial community, and k represents the half-saturation constants for $Hg^{(II)}$ and SO_4 uptake (Watras et al. 2006). The expression can be expanded to include other substrates that may limit SRB activity, such as organic carbon, nitrogen or phosphorous.

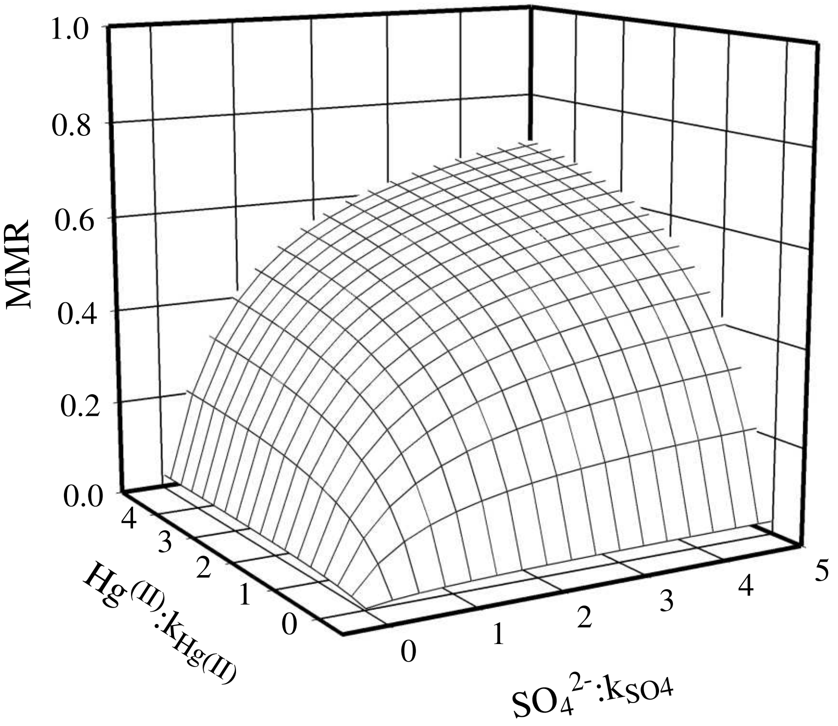


FIGURE 14. THEORETICAL RELATIONSHIP BETWEEN MERCURY METHYLATION RATE (MMR) AND TWO KEY SUBSTRATES, INORGANIC MERCURY AND SULFATE (SOURCE: WATRAS ET AL., 2006).

The response surface depicted in Figure 14 further illustrates two major points about mercury methylation. First, that relatively large changes in methylation rates occur at low substrate concentrations (i.e., above threshold but below saturation). This point is relevant for remote, relatively pristine receiving waters like those in the PGIR where the concentration of key substrates is near limiting levels. Second, and perhaps more importantly, that limiting substrates interact synergistically. Thus, increased inputs of sulfate and inorganic mercury would have a disproportionately larger effect together than either would have separately.

Quantitative predictions of mercury fate and transport should consider:

- Mercury present in surface waters used during processing, both dissolved and that present in suspended sediment.
- Mercury present in groundwater used in processing.
- The range, distribution, and chemical form of mercury present in mined strata, as determined from core samples.
- The range of mercury present in tailings.
- Mercury present in runoff waters from tailings stockpiles and in waters of retention ponds.
- Mercury present in green taconite pellets.
- Mercury predicted or measured in stack emissions, followed by estimates of the proportion deposited locally vs. that entering the global atmosphere.

SELENIUM

Selenium (Se), a nonmetallic element is an important trace nutrient in animals but a potential toxin at higher concentrations. Selenium pollution results from a number of human activities, including coal burning and mining (Lemly 2004). Selenium has geochemical behavior similar to that of sulfur, so it is commonly present in small amounts in pyrite. Destabilization of sulfide minerals can mobilize selenium (McNeal and Balistrieri 1989). The behavior of dissolved selenium is largely controlled by the pH and redox conditions in the environment. In most aquatic and soil environments selenium occurs as selenate $(SeO_4)^{-2}$, which is soluble and biologically available, or as selenite $(SeO_3)^{-2}$, which is immobilized by strong adsorption to iron oxides in the pH range of 2 to 8 (Howard 1977). Because of this strong affinity for particulate matter, it is possible for sediment Se concentrations to be elevated even when aquatic concentrations are low (Lemly and Smith 1987).

Selenium is highly bioaccumulative. Oxidation and methylation in sediments renders Se available for biotic uptake, and is introduced into the food chain by rooted plants, benthic invertebrates, and bottom-feeding fish (Lemly and Smith 1987). Selenate, selenite, and organoselenium compounds all exhibit varying degrees of bioaccumulative potential, and different organisms bioaccumulate each form differently as well (Besser et al. 1993). Generally, bioaccumulation is most extreme at the lowest trophic levels. For example, periphyton bioconcentrate selenium by a factor of greater than 1000, whereas mayflies feeding on the periphyton biomagnified the selenium by another factor of 2.2 (Conley et al. 2009). While diet is the dominant exposure pathway for higher trophic level organisms, some direct uptake of selenium compounds may be important as well (Besser et al. 1993). Selenium pollution results in reproductive failure in higher trophic level organisms, manifested as larval deformities in fish and embryo failure in birds (Lemly 1987; Chapman et al. 2009).

Because of the bioaccumulative nature of selenium, it is widely recognized that traditional methods of toxicity testing are not adequate for assessing selenium impacts, and that site-specific risk assessments are required (Chapman et al. 2009). Dissolved selenium concentrations are poor indicators of selenium pollution and toxicity, and concentrations in fish tissue (and ideally, fish and bird eggs and sediments) should be monitored as well. Recognizing this, the EPA has recommended a chronic criterion based on fish tissue concentrations of 7.9 ppm dry weight. However, this figure has been controversial (Renner 2005). In an open letter to the EPA, five toxicologists, including the author of the study from which the 7.9 ppm value was derived, suggested this concentration is too high to adequately protect biota. A lower criterion of 5.85 ppm dry weight has been suggested (Skorupa et al. 2004; Renner 2005). However, due to the complex biogeochemistry of selenium, the impact of selenium contamination on an ecosystem is a function of local geochemistry, hydrology, biology, and other factors. Some evidence suggests substantial differences between selenium toxicity in streams and lakes (Simmons and Wallschlager 2005) as well. Nonetheless, the existing chronic (i.e., long-term exposure) water concentration criterion of 5 µg/L set by the EPA has been adopted by a number of states, including Wisconsin.

Acute selenium toxicity occurs at fairly high concentrations. The LC50 (the concentration that will result in the mortality of 50% of the population) for many aquatic organisms is greater than 1 mg/L (Brix et al. 2000). The current EPA acute (i.e., short-term exposure) criterion is provided as a function of the relative contribution of selenate and selenite to total selenium. The acute toxicity of selenium has been shown to be strongly linked to ambient sulfur concentrations as well (Brix et al. 2000). While Wisconsin does not currently have a standard for acute selenium toxicity, the Michigan acute aquatic life standard is 120 µg/L. The Wisconsin human threshold criterion for public water supplies is 50 µg/L.

While selenium contamination is commonly associated with sulfide mining, and is also a major concern in areas impacted by mountaintop coal mining (Palmer et al. 2010), selenium contamination has also recently been discovered at the Tilden and Empire taconite mines on the Marquette range in northern Michigan (MDEQ 2009; 2010). Extensive sampling in the vicinity of these mines found many exceedances of the 5 µg/L chronic criterion in surface waters. The acute criterion (120 µg/L) was not exceeded in streams or lakes, but was exceeded in a seep coming out of a reclaimed waste rock pile. Selenium concentrations in sediments were measured as high as 39 mg/kg; a maximum of 2 mg/kg has been recommended as protective of bioaccumulative risk (MDEQ 2009). Fish tissue concentrations were measured at levels well in excess of the EPA criterion near the mines as well (MDEQ 2009; 2010). Interestingly, although the two mines are directly adjacent to one another, selenium concentrations in waste rock seeps at the Empire mine are two orders of magnitude greater than those from waste rock seeps at the Tilden mine (MDEQ 2009), suggesting spatial heterogeneity in the distribution of selenium in ore bodies. Given the scale of open-pit taconite mines, therefore, the absence of selenium at one location in the mine pit does not necessarily imply that it is not present elsewhere.

Due to its long life in the environment, selenium pollution is difficult to reverse; prevention is key (Lemly 2004). Baseline site characterization should include selenium measurements in fish and bird eggs, fish tissue, and sediments. A survey of historic iron mines in northern Michigan found elevated selenium (7 mg/kg) in pond sediments at one site out of four sampled (MDEQ 2010), indicating that selenium leaching is not unique to the Empire and Tilden mine site. It should be treated as a potential contaminant of particular interest, especially in locations where sulfide minerals are present.

MINERAL FIBERS

“Asbestos” is the generic name for the silicate materials chrysotile, actinolite, amosite, anthophyllite, crocidolite, and tremolite (NTP 2011). Extensive use of these materials in industrial applications and materials began in the late nineteenth century and peaked in the mid-1970s. Asbestos is now recognized as a serious human health hazard (Section 3.1), and therefore its use and production has been greatly reduced. Asbestiform minerals form under special geologic conditions characterized by folding, faulting, shearing, and dilation; these deformations can also create other, non-asbestiform fibrous minerals (Ross et al. 2008). Several faults and folds occur on the eastern end of the Biwabik iron range in northern Minnesota (Ross et al. 2008), and amphibole fibers have long been known to exist at the Peter Mitchell mine located there (previously Reserve Mining Company, now operated by Cleveland-Cliffs as Northshore Mining Company).

Mineral fibers played a central role in a widely publicized legal battle over the operation of the Reserve mine. Up until the late 1970s, this operation discharged tailings into Lake Superior at Silver Bay, MN. However, following the discovery of the fibrous materials cummingtonite and grunerite throughout the western arm of the lake and in drinking water in Duluth and surrounding municipalities, Northshore was ordered to convert to land-based tailings disposal and fund the construction of water filtration systems (Berndt and Brice 2008; Durhum and Pang 1975). Grunerite, an iron-rich amphibole, sometimes occurs with a fibrous crystal habit. This asbestiform grunerite, amosite, has especially slender crystals with a length:width aspect ratio of more 5:1, and is a known hazard linked to mesothelioma (e.g., Walton 1982). Following the controversy, however, many questions remained as to whether any of the fibers were in fact amosite, if ingestion of mineral fibers was dangerous, and if the non-asbestiform fibers presented a health risk (Berndt and Brice 2008). The long latency of asbestos-related illness made this last question particularly difficult to answer. Human health risks related to airborne mineral fiber exposure are discussed further in Section 3.1.

A recent mineralogical study by Ross et al. (2008) concluded that ore from the Peter-Mitchell mine contained the amphibole minerals cummingtonite, grunerite, actinolite, and hornblende, and the actinolite is a low temperature alteration of a non-fibrous amphibole, rather than true asbestos. Currently, the Northshore mine is required to measure fibers (subcategorized as amphibole, chrysotile, non-amphibole/non-chrysotile, and ambiguous) at surface water monitoring stations by its National Pollutant Discharge Elimination System (NPDES) permit, and in some locations a limit is imposed on the concentration of amphibole fibers.

The metamorphosed iron formations in Wisconsin commonly contain amphibole minerals. Grunerite is present in iron formations of the Black River Falls District, the Florence District, and locally in the Penokee-Gogebic District in Wisconsin. In the Penokee-Gogebic District grunerite is known to occur where the Ironwood Formation has been contact metamorphosed by igneous intrusions (Schmidt 1980), although there are no published studies of the aspect ratio or possible health effects of the grunerite in this district.

OTHER METALS OF CONCERN

Many of the transition elements have geochemical behavior similar to that of iron and therefore are commonly present in trace amounts in iron oxide and iron sulfide minerals. Magnetite commonly contains Mg, Ti, V, Cr, Mn, Co, Ni, Cu, Hg, and Zn. Pyrite commonly contains Ni, Co, As, Cu, Zn, Ag, Au, Tl, Se, and V. The concentration of these metals varies within each deposit and the fate of the ions during taconite processing and waste rock storage would depend on the beneficiation processing and on the geochemical and microbiologic processes acting on the rock after being mined.

Species- and community-level effects of elevated concentrations of specific metals have been documented. For example, zinc pollution has been shown to shift the algal community from one dominated by diatoms to one dominated by green or blue-green algae (Genter et al. 1985). In one study, diatom deformities increased from 0.2 to 12% of the population when exposed to heavy metals, with the genus *Fragilaria* most affected (McFarland et al. 1997). Additional ecological impacts related to elevated metal concentrations in surface water are discussed in Section 2.3.

MAJOR NUTRIENTS

The weathering of minerals that contain plant nutrient ions can contribute to eutrophication in surface water. Phosphorus is present in the Ironwood Formation and overlying Tyler Formation in the Penokee Range in Wisconsin. Limited sampling has indicated concentrations averaging 0.167 wt. %, which is high enough to contribute to eutrophication (Bjornerud et al. 2012).

SUSPENDED AND DISSOLVED SOLIDS

Fine-grained mineral particles that become suspended in moving water are a common issue in surface water at sites where sediment and soil is disturbed or fine-grained crushed rock is produced. Broken waste rock is generated in iron mining operations from overburden formations, from uneconomic zones within ore bodies, and from fine-grained quartz-rich tailings remaining after removal of magnetite or hematite from the ore. Fine-grained particles from these sources can become suspended in surface water and increase the water's turbidity if adequate control measures are not implemented.

ORGANIC COMPOUNDS

Mining operations require a great deal of heavy machinery, and therefore utilize a large quantity of fuel, lubricants, solvents, etc. Fuel oil is also commonly used along with ammonium nitrate fertilizer for blasting. In operations where chemical flotation is employed, a variety of organic surfactants are typically used in the process (see Section 1.3). Any organic compounds being utilized in a mining operation should be monitored for in surface and groundwater, especially at any storm and process water outfalls.

2.3. AQUATIC ECOLOGY

There is a paucity of scientific literature on the specific impacts of iron mining on aquatic ecosystems. However, a survey of the broader literature indicates that mining activities have demonstrably altered species composition and indicators of whole-ecosystem health (e.g.,, biodiversity). Species-level effects of pollution seldom occur in isolation; any changes in the community structure can resonate through the food web as changes in the primary producers influence the primary and secondary consumers which in turn can impact the fish community. Bioaccumulation is also a factor, and grazers and filter feeders are often particularly sensitive, because they ingest periphyton and organic matter which are typically enriched with metals and other pollutants (Besser et al. 2007). Ecological evidence of mining-related pollution can often be found in the composition of the algae and macroinvertebrates.

Periphyton (i.e., benthic algae) have been shown to be sensitive to elevated metals concentrations both *in situ* and in laboratory settings. The most common metals of concern are copper, zinc, and lead. Many field studies have identified periphyton sensitivity at zinc and copper mines, and a study in the Cornwall region of England found similar results at lead and copper mines (Foster 1982). There is generally a loss of sensitive taxa, primarily diatoms, and a reduction of species diversity and taxa richness with elevated heavy metal concentrations (Beech et al. 1972). In one study, there was approximately a 40% reduction in algal species downstream from mining operations (Deniseger et al. 1986), and similar results were found in a downstream lake (Austin and Deniseger 1985).

Macroinvertebrates are also sensitive to pollution from heavy metals, acid mine drainage, and increased sediment loads (Freund and Petty 2007, Bruns 2005, Poulton et al. 2010). Studies in the Appalachian Mountains have found reduced taxa richness and a reduction or elimination of sensitive macroinvertebrate species (Bruns 2005, Freund and Petty 2007, Pond et al. 2009). A study in Sweden (Malmqvist and Hoffsten 1999) also found a reduction in the abundance of sensitive species in streams below mine sites, although in this case there was not a reduction in total abundance or biomass. Copper and zinc were identified as being of particular concern.

3. HUMAN HEALTH CONSIDERATIONS

Taconite mine tailings and waste contain components having well-documented toxic properties (Plumlee and Morman 2011). These may include, depending upon the ore formation, mercury and other metals, asbestos and other mineral fibers, arsenates, sulfates, and silicate dusts. In most cases, the documented incidence of toxicity is to on-site workers or to the public living very near to poorly-managed operations.

Risk to the public off-site is dependent upon the off-site presence of toxicants, via an appropriate exposure pathway, at concentrations sufficient to cause harm from either a short term (acute) or long-term (chronic) duration. The exposure pathway could consist of changes to local air quality (inhalation), changes to surface- or ground- drinking water sources, direct contact via contaminated surface waters, or direct contact to contaminated soils or stockpiles. Risk to the public could also follow an indirect route of environmental impacts resulting in exposure to toxicants in food, as well as loss of livelihood (e.g., subsistence needs such as wild rice and fishing, loss of tourism, etc.).

3.1. HEALTH RISKS RELATED TO AIR QUALITY

Particulate emissions

Particulate matter (PM) is a term for microscopic solids in the form of inhalable aerosols. PM may be from various dust or combustion sources. PM also forms in the atmosphere from condensation of atmospherically transformed volatiles, and may be transported great distances once formed or emitted. PM is of public health significance due to the small and inhalable size, varying chemical reactivity and toxicity, and their potential to be transported in the atmosphere. PM released from taconite mining operations would fall into overlapping size ranges corresponding to the process source of the PM. Inhalable suspended and windblown dust from construction activities (ore removal, crushing, and grinding, road construction, road dust, etc.) would likely fall into the 1-100 micrometer (μm) range, with particles less than 4-10 μm diameter being of concern due to the potential for this size range to reach the bronchiolar and alveolar depth of the lungs. "The largest source of PM from taconite ore mines is traffic on unpaved haul roads. Other significant PM emissions at taconite mines are tailing basins and wind erosion" (USEPA 1997a). To the extent that local and regional PM in air surrounding the mines is influenced by mined materials, this impact would need to be predicted based upon the composition of those materials.

PM aerosols less than 2.5 μm tend to be from combustion and stack sources, with heat curing of taconite pellets being an obvious source of gas-phase and particulate emissions, both from the heating fuel and the pellet curing. Product transport and construction vehicle exhaust are another source of air emissions. In addition, the substantial electrical energy requirements of taconite processing must also be considered as part of the air impact equation. Additional atmospheric contributions (PM as well as other air pollutants) from electrical generation stack sources would likely be regulated within the context of state air management and emission permitting.

MINERAL FIBERS

Asbestos is considered a human carcinogen by the U.S. Department of Health and Human Services (DHHS), the U.S. EPA, and the International Agency for Research on Cancer (IARC) (ATSDR 2001), causing respiratory-tract cancer, mesothelioma of the lung and abdominal cavity, and other cancers (NTP, 2011). The incidence of asbestos-related pulmonary disease, including malignant mesothelioma, typically follows chronic exposure. The potential presence of asbestos in its various forms in ore and waste rock (as discussed in section 2.2) raises the need to understand whether mineral fibers are present in proposed Wisconsin taconite ore sites. The assessment of a proposed mine site should include steps to protect both workers and public health by preventing dispersion and conducting confirmation monitoring. Confirmation monitoring should particularly emphasize the protection and reassurance of nearby communities.

Environmental concentrations are used as comparison values in assessing asbestos. The Toxic Substances and Disease Registry *Toxicological Profile for Asbestos* (ATSDR 2001) reports typical asbestos levels in rural air of about 0.00001 fibers/mL (10 fiber/m^3), with typical levels found in cities being about 10-fold higher. Close to an asbestos mine or factory, levels may reach 10,000 fibers/m^3 (0.01 fibers/mL) or higher.

Questions are anticipated regarding the public health assessment of asbestos and asbestos-containing material (ACM) in the environment around a taconite mine. The following summary, previously published within an assessment of a Wisconsin property, is offered as an initial perspective on acceptable levels of asbestos in air and soil (ATSDR 2008):

> *ACM. Standards for the various definitions of asbestos-containing material and the handling of those materials are presented under The Wisconsin Administrative Code, ch. NR 447.02 (WAC 2004). In general, ACM would contain at least 1% asbestos as determined by polarized light microscopy (PLM) and would be classified as friable or non-friable. Therefore, the 1% asbestos criterion is a regulatory definition that corresponds to the detection limit for the PLM analytical method. It is used to make decisions regarding the disposition of asbestos-containing waste materials. It is not a health risk-based concentration that determines whether a material could pose a health hazard resulting from possible exposure.*
>
> *Ambient Air. EPA and ATSDR have not published health-based standards and guidelines for asbestos in air, but the ATSDR Toxicological Profile for Asbestos includes a summary (ATSDR 2001, Table 6-4) of typical general and occupational exposures. Clearance levels and action levels for indoor air were developed by EPA for the World Trade Center Response (EPA 2004), but are not cited here as the exposure and risk scenario for outdoor air differs from indoors. In addition, risk-based screening criteria for other sites that EPA and ATSDR have investigated have been developed for residential exposure situations. [....] NIOSH (2005) recommends that occupational exposures be reduced to the lowest feasible concentration, and recommends a relative exposure limit of 0.1 fiber/cc, as determined by NIOSH Method 7400.*
>
> *Soil. Health-based standards and guidelines for safe asbestos concentrations in residential soil have not been established. DPH [WI division of Public Health] acknowledges, as does EPA in their 2003 report [EPA 2003], that it is difficult to predict concentrations of asbestos in air resulting from soil contamination due to the variety of factors affecting the dispersion of soil dust. Any remedial actions will need to address appropriate clean-up criteria based on anticipated future land use.*

Mesothelioma Rates have been studied in taconite mining regions of northeast Minnesota (MDH 2007):

> *Four previous reports from the Minnesota Department of Health (MDH) have examined cancer rates in NE Minnesota. While overall cancer rates have been comparable to statewide rates, a statistically significant excess of malignant*

> *mesothelioma among males has consistently been found in NE Minnesota. The findings from these previous reports are summarized in Table 1. The last row of the table shows the results from the most recent update through 2006. As with the previous analyses, the mesothelioma rate among males remains approximately two-fold higher than the state average for the period 1988-2006 (146 cases vs. 69 expected cases). Among females, the rate remains slightly (30%) lower than the state average (13 cases vs. 18 expected), although this difference is not statistically significant.*

The report continues:

> *As has been discussed since the first NE cancer report (MCSS [Minnesota Cancer Surveillance System], 1997), the large excess among males is consistent with an occupational exposure. Most of this excess appears attributable to two large and unique industries in NE Minnesota – iron ore mining and processing and the manufacturing of asbestos-containing ceiling tiles (Conwed Corporation plant in Carlton County). Workers in both industries experienced potential exposures to commercial asbestos, although the role of other mineral dusts in the taconite industry remains under investigation. As described further below, due to previous efforts to identify workers employed in these industries and to the statewide cancer registry, it has been possible to compare these records and ascertain to what extent mesothelioma cases in NE Minnesota (or anywhere else in the state) were previously employed in these industries. Some 43 of the 58 mesothelioma cases among miners, and 23 of the 25 cases among former Conwed workers were residing in NE Minnesota at the time of diagnosis. Since three cases worked in both industries, at least 63 male cases, or 82% of the excess cases among males in NE are attributable to these industries. The actual contribution is likely to be even higher since the databases containing the rosters of workers are not complete and include many records with missing or erroneous demographic data (such as social security number or date of birth) that is used in matching records.*

A study of workers at a gold mine in South Dakota where nonasbestiform amphibole minerals were present concluded there was not a significantly increased risk of cancer mortality linked to exposure, but that there were significant excesses of tuberculosis, silicosis, and other diseases related to silica exposure (Steenland and Brown, 1995).

3.2. HEALTH RISKS RELATED TO DRINKING WATER QUALITY

Soluble substances in stored waste rock, tailings, or tailings impoundments have the potential to affect ground or surface drinking water supplies if not properly managed. Acid formation is a concern if waste rock and tailings from taconite mining contain metal sulfides (section 2.2). Although this section is concerned with Public Health, acid formation has related effects on ecosystems. These include both direct pH effects, and indirect effects caused by enhancing the introduction, through solubilization, of mineral and cationic toxicants into aquatic systems. From the public health perspective, the greatest concern would be the potential for the pH-enhanced alteration of drinking water supplies, with emphasis on unhealthy concentrations of metals in drinking water. The effect metals have on drinking water varies with the specific contaminant, and may range from acute or chronic toxic concentrations to aesthetic effects on taste or appearance that render water unpalatable. Although metals vary in their mechanism of toxicity, one shared feature is environmental or biological persistence. This is because metals, which may exist naturally in various mineral forms, tend to exert their biological effects as ionized elements or in relatively simple organometallic chemical forms. Acid leaching of metals predictably makes them more soluble and bioavailable.

If significant sulfide minerals are present, aqueous sulfate (sulfuric acid) formed primarily from weathered pyrite (see section 2.2) can drive low-pH conditions in tailings impoundments, surface runoff, and infiltrated runoff that enhances solubility and leaching of metals waste rock and wastewater impoundments.

Protection of Groundwater/Drinking water. To assess the potential for groundwater impacts to private and municipal drinking water supplies, a complete profile of the leachable mineral content of representative samples of the ore and waste materials that might be generated as part of a mining operation is required. Prior to commencement of mining activities at a new site, it is important to establish a thorough baseline profile of potentially affected groundwater and drinking water aquifers. Both the ore and waste material sample profiles and the water profiles should include, but not be limited to, minerals containing As, Cu, Hg, Al, Se, B, Fl, Sr, Mn, Ni, and Zn. In addition, basic chemistry (pH, hardness, etc.), sulfur species, and mineral fibers should be measured. Once mining begins, similar profiles should be regularly generated from tailing leachate, and from tailings pond supernatant and sediment.

The ore removal and processing facility should have a preparedness plan for unplanned spills of process chemicals, including, but not limited to fuel, flotation chemicals, surfactants, acids, ore wash, and suspension fluids. The preparedness plan should have specific contingencies to prevent groundwater and surface water contamination in the event of a spill.

Much of what is currently known about leachable materials generated from taconite mining has come from studies of surface water and groundwater around "pit lakes" formed within old or abandoned mine sites such as the Mesabi Nugget mine near Hoyt Lakes-Aurora MN, where manganese and arsenopyrite have been identified as contaminants of concern (J. Walsh, Minnesota Department of Health, personal communication with R. Thiboldeaux). The pit lakes tend to be in remote areas away from exposure routes to the public, but such impacts to groundwater should be considered with respect to land reclamation and reuse. For new mining sites, detailed watershed, groundwater, and well use maps are useful tools for assessing impacts, and should be among the information needed to review a mine permit application.

SELENIUM

Selenium has been identified as a component of taconite waste leachate with a potential to affect groundwater (MDEQ 2009; 2010). Selenium, an essential nutrient for humans, can be harmful when consumed in excess. Wisconsin's Public Health Groundwater Quality Enforcement Standard for Selenium is 50 µg per liter, with a preventative action limit of 10 µg/L (Wisc. Admin. Code, *ch.* NR 140). The element selenium "is not often found in the environment in its elemental form, but is usually combined with other substances. Much of the selenium in rocks is combined with sulfide minerals or with silver, copper, lead, and nickel minerals" (ATSDR 2003).

Selenium is readily absorbed when consumed orally as selenite, selenomethionine, selenocystine, and selenate. However, the uptake mechanisms and pharmacokinetics varies by selenium species. Similarly, the observed bioaccumulation of selenium varies, with selenomethionine > selenite ≈ selenate (reviewed in ch. 6 of ATSDR 2003).

Since selenium, depending upon the dose, is both an essential nutrient and a toxicant, understanding intake boundaries are appropriate. The current Recommended Daily Allowance (RDA) for selenium is 55 µg/day for male and female adults. This RDA is established by the Food and Nutrition Board of the National Research Council (National Academy of Sciences). The current NAS Tolerable Upper Intake Level (UL) for selenium is 400 µg/day for adults (or approximately 5.7 µg/kg/day) (ATSDR 2003).

Chronic oral exposure to excess selenium (10-20 times above normal intake, regularly consumed over two years or more), as might occur through contaminated residential drinking water, can result in selenosis (ATSDR 2003). The effects of selenosis include diseased skin and nails, hair loss, unsteady gait, and paralysis. Acute effects result from oral exposure to levels several thousand times greater than normal intake, with symptoms that include gastrointestinal distress and tachycardia. Lethal does to selenium studied in rodents are on the order of 2-50 mg/kg/d. No-effect levels in rodents appear to be typically less than 1 mg/kg/d (various studies cited *in* ATSDR 2003- ch. 3). Selenium has not been implicated as a carcinogen.

MINERAL FIBERS

Small amounts of asbestos are sometimes present in drinking water from various sources including natural deposits, asbestos in mine waste, or asbestos in cement pipes and filters (ATSDR 2001). The effects of exposure to asbestos via oral consumption are not defined as confidently as are those via inhalation. A 1983 literature review suggested there was no clear evidence of carcinogenic effects of asbestos ingestion (Condie, 1983). The U.S. EPA Maximum Contaminant Level Goals (MCLG) for asbestos is 7 million fibers per liter of long fibers (length greater than or equal to 5 µm) that may be present in drinking water (USEPA 2012a). Seven million fibers per liter is also the Wisconsin Groundwater Quality Standard for asbestos (Wisconsin Administrative code, ch. NR 140).

3.3. POTENTIAL IMPACTS ON FOOD SAFETY AND AVAILABILITY

MERCURY IN FISH

The release of mercury into the atmosphere from both natural and industrial sources is a concern due to its direct or indirect deposition to surface waters, followed by the chemical or biochemical transformation to methylmercury, a well-characterized developmental neurotoxin (ATSDR 1999), and ultimately the uptake and bioaccumulation of methylmercury in the food chain. Consuming fish that have accumulated methylmercury are a health risk, particularly to women of child-bearing age. It is recommended that consumption of fish caught from waters statewide be restricted according to the DNR safe-eating guidelines, and exceptions (e.g., stricter guidelines) are in place for numerous lakes throughout northern Wisconsin due to higher levels of mercury in fish from these waters. For example, in Ashland County, consumption advisories due to mercury in fish are listed for English, Moquah, Spider, and Spillerberg Lakes (WDNR 2012).

WILD RICE

Wild rice is a natural resource of particular concern in both the region of the Minnesota iron ranges and northern Wisconsin. Since 1973 Minnesota has had water quality standards specific to the wild rice resource (MPCA 2011). As summarized in *Minnesota's sulfate standard to protect wild rice* (MPCA 2013):

> *Wild rice is an important component of aquatic communities in parts of Minnesota, particularly northern Minnesota. It provides food for waterfowl, and shelter for animals and fish. Wild rice is also a very important cultural resource to many Minnesotans, and is economically important to those who harvest and market wild rice.*
>
> *Sulfate is a natural chemical commonly found in air, soil and water. It can be found at varying concentrations in discharges from permitted facilities such as mining operations, wastewater treatment plants and other industrial facilities. The primary factor in sulfate loading to surface water is the surface geology of Minnesota. For example, the glaciers left relatively high-sulfur soils across southwestern Minnesota, which contribute sulfate to lakes and streams.*
>
> *Past studies have shown that wild rice is primarily found in waters with relatively low sulfate concentrations. In 1973 Minnesota adopted a standard to protect this important resource. This 10 mg/liter sulfate standard, which is found in Minnesota Rules 7050.0224, subpart 2, protects "water used for production of wild rice during periods when the rice may be susceptible to damage by high sulfate levels." This standard applied to both natural stands of wild rice and commercial paddy rice fields.*

It should be noted that Minnesota's wild rice sulfate standard is currently based on observational studies. A two-year MPCA/University of Minnesota study (2012-2013) to more rigorously evaluate the standard is in its final stages. This study includes field surveys, literature review, mesocosm experiments, sediment incubations, and toxicity testing. Following experimentation, the standard will potentially be revised according to EPA Tier I methods (MPCA 2013). Because Wisconsin does not currently have a sulfate standard for wild rice protection, the results of this effort can potentially be used to establish permit limits.

4. SOCIOECONOMIC CONSIDERATIONS

4.1. SOCIOCULTURAL CONSIDERATIONS

There is a dearth of literature on the sociocultural aspects of mining. A search of the published literature using key word combinations of mining, taconite, public opinion (attitudes, concerns) and society revealed little documentation. Clearly a deeper understanding of the public's perceptions of mining is needed. Thus this section a) summarizes the findings of two applicable studies, and b) provides an overview of the methods with which the public perception of mining in Wisconsin may be explored.

The conclusions of one paper are applicable, though the geographic and resource-extraction context are different from Wisconsin. Richards and Brod (2004) investigated how rural communities confront development proposals that involve uncertain risks. Specifically, they investigated community support (differentiating community leaders from residents) for a gold cyanide process (GCP) mine in Montana. They conclude with a recommendation that rural communities facing projects characterized by new and unfamiliar technology should approach these developments as "*new species of trouble* (Erickson, 1994) that can be more fully understood through case comparisons."

The literature on the social positions of rural community leaders documents that leaders tend to be better educated, are business owners, own more land and have more responsibility for community development than residents. The authors' findings are consistent with the literature. Their community leaders, more so than residents, "anticipated personal gains from the mine and that the economic benefits of the project would benefit the community and outweigh the economic costs."

As might be anticipated, community leaders in the Richards and Brod study supported the proposed mine more strongly than did residents. However, disparity in leader and resident support for the mine dissipated as perceived personal economic interest in the mine increased. Conversely, opposition for the mine increased for both leaders and residents as perceptions of environmental contamination grew. Given that community leaders tend to have greater responsibility for potential impacts of risk developments (e.g., mines) and tradeoff decisions of risks versus benefits are made at the lowest level of government it isn't surprising that Richards and Brod found that leaders exhibited stronger trust (i.e., less recreancy) in county government than residents. Further, community leaders exhibited lower levels of trust (higher levels of recreancy) in environmental groups and university scientists than did residents. The authors explain that leaders were more likely than residents to want to protect the role of local government in regulating and controlling the mine permitting process. In other words, leaders oppose outside interveners more so than do residents because of their desire to maintain a degree of local empowerment. The importance of local trust in support of a high risk development cannot be discounted; its influence on support even exceeded that of the influence of potential economic benefits.

A second paper comes from Sweden. It presents an applicable understanding of the fragile issue of introducing major environmental changes into a rural residential area. Pedersen and Johansson (2012) explored community response to anticipated changes in the local environment resulting from a wind farm and exploratory uranium drilling as they related to factors predicting beneficial or adverse appraisals of environmental changes. The study took place in a setting analogous to northern Wisconsin; an inland rural setting with low population density that included scenic qualities and recreation opportunities. Residents lived in dwellings on or very near lakes or forests which provided opportunities for hunting and fishing. The authors note that an individual's appraisal of environmental change is influenced by his or her previous experiences and attitudes towards the sources of stress. Consequently, introducing technical or industrial activities (e.g., wind farms or uranium drilling in Sweden or a taconite mine in Wisconsin) to such an environment could be appraised as threatening. A succinct summary of their findings is that psychological factors such as concerns for the environment (exhibited as pro-environmental behavior), valuing closeness to nature and involvement in town meetings (intended to assist with appraisal) can actually hinder the appraisal process and should be considered when new developments affecting the environment are presented.

The latter point requires elaboration. The exploratory uranium drilling was opposed by the residents despite its long-term economic growth potential. The authors explain that a uranium mine (as an outcome of successful exploratory drilling) would be a major change to the environment so the perceived threat to a resident's closeness to nature would overshadow any societal gains. Further, bonding with nature is independent of length or residency in the area; results from this study and others cited by the authors, found that duration of residence was not associated with appraisal of a proposed environmental change. Residents, regardless of how long they lived in the community, were not willing to sacrifice their opportunities to be close to nature for societal economic gains or energy-related environmental changes.

Further, the authors' hypothesis that residents' participation in information meetings would assist with their beneficial appraisal of an environmental change was not consistently supported. In some instances, the participatory method backfired; participating in the meeting did not shift the outcome in a more favorable direction. In fact, information released by the developers actually strengthened the objecting views of the residents and those who attended the drilling meeting ended up being more opposed to exploratory drilling than those who did not attend.

METHODS OF SOCIAL INQUIRY

This section briefly identifies methods which could be called upon for exploring the sociocultural aspects of mining in Wisconsin. It is not a "how-to" instruction guide. Its purpose is to assist researchers with the application of the correct "tool" for various opportunities and situations. Appendix A lists 21 references on the conduct of social inquiry.

The methodology utilized by Richards and Brod (2004) included a combination of qualitative interviews to help define the issues and add context to later findings and random sample surveys to quantify opinions, preferences and attitudes which can then be projected out to the larger populations. Their approach is the ideal standard practiced by DNR social scientists and one which we would recommend to those conducting social inquiries on behalf of or tasked by the DNR.

Focus groups

Focus groups are conducted by engaging a group of respondents in a conversation which is of interest to the researcher. The participants possess a level of homogeneity such that they are similar to one another in a way that is germane to the research question. The discussions consist of a small group of people (typically six to ten) sitting around a table discussing a topic under the direction of a trained moderator. Discussions typically last 90 to 120 minutes. The moderator strives to create a nonjudgmental environment so as to make the participants more willing to openly share their opinions and ideas (Klofstad, 2004). The discussions are relaxed, informal, and generally enjoyable for the participants. The format allows participants to share their experiences and express their feelings and opinions. During the discussion they have the opportunity to listen to others, to compare their experiences and ideas, and to interact with one another. A single discussion is rarely sufficient; the approach typically requires the conduct of multiple groups in order to discover potentially meaningful trends across the groups and differences between the groups (e.g., focus groups in north Wisconsin community could include a group of long-time residents, new transplants from urban areas, members of environmental groups, members of hunting and fishing groups). Though planned and pre-tested, because focus group participants are engaged in a semi-free discussion, the researcher does not have complete control over the flow of the conversation. This free-flow characteristic can be a benefit to data collection because it can uncover topics previously unknown to the researcher. Surveys, which isolate respondents, and which also limit their answers to closed-ended questions, do not provide respondents with this flexibility. As a method of collecting information, focus groups have their limitations. They generate narrative rather than numerical data; insights rather than statistical generalizations. Certain themes, however, typically recur in ways that suggest they may be widespread throughout the population of study. The more open approach of a focus group allows the researcher to discover matters of greatest interest to the participants. Such data can assist with the development of a more formally structured questionnaire and if so done, used to add context to researcher interpretation of data generated by the conduct of a survey.

In-depth personal interviews

An in-depth personal interview is a method of collecting data on the attitudes and behaviors of individuals through some form of conversation between the researcher and a respondent (Klofstad, 2004). Interviews can be formal (e.g., within the chambers of an elected official's office) or less formal, often conducted on-site (e.g., at a campground or boat launch). The latter setting is a unique asset of the personal interview in that data are timely; data collected directly from the individual who currently or recently experienced the phenomenon under study. Further, the approach opens the door to participant observation (taking a simplified ethnographic approach) by allowing (when possible and desirable) the researcher to interact with the subject in order to gain a deeper understanding of the phenomenon.

Like a focus group, in-depth personal interviews generate narrative rather than numerical data. Although results may reflect the attitudes and opinions of a community atlarge, their strength is providing deeper understanding from information-rich informants. Thus a purposive and "snowball" approach is frequently taken by the researcher. For example, exploring the opinions and attitudes towards mining in northern Wisconsin could include in-depth personal interviews with key informants such as the mayor, town board members, members of the Chambers of Commerce, local business and industry leaders (e.g., timber companies) and agricultural producers. These key informants would likely suggest additional informants (i.e., the "snowball" effect) to be interviewed. Additionally, in-depth interviews could be conducted on site at potentially at-risk locations and in conjunction with various activities (e.g., interviews with anglers at lakes, streams and rivers and hunters and silent-sport enthusiasts on public lands). Also similar to focus groups, information generated from personal interviews can be applied to the development of a statistical survey and provide context to the interpretation of its results.

Surveys[1]

Survey research is a method of data collection that allows a researcher to gather information on the opinions, attitudes, experiences and attributes of individuals. The data collected from these individuals are often analyzed using statistical methods and software in order to isolate trends,

---

[1] Introduction to Survey Design and Delivery, NOAA Coastal Services Center, 2007, is recommended as a general reference for the conduct of survey research.

correlations and causal connections on a given topic of study. The NOAA Coastal Services Center (2007) explains that the "most important component of any successful survey project is to have a strong study conceptualization. Conducting a survey is much more complex than just asking a group of people a series of questions to try to solve a problem or better understand an issue. Rather, a survey is a systematic examination of a population by means of a series of specific, targeted questions. These questions should possess direct application in solving an identified problem or issue. The development of a survey simply for the purpose of determining what people think (e.g., pleased, displeased, concerned, happy, etc.) often generates data that are of limited utility." For example, a survey can help identify the relationships between a northern Wisconsin community, its natural resources and a development project which could put those resources and community life at risk.

Quantitative surveys should be used when the researcher needs to gather the same type of information from a larger group of people. Random sample surveys are most common and are designed to make statistical inferences about the population at large. Unlike focus groups and personal interviews, the conduct of a survey is intended for generalizability – results that are statistically representative of a population. This method can be problematic if the researcher is not familiar with various sampling protocols (e.g., when to apply simple random sampling versus stratified sampling) or if the researcher has not adequately considered what questions to ask, how to ask them or if deeper qualitative information is required.

Surveys can be administered in a variety of ways, but are typically divided into two categories: interview-based and self-completed. Common interview-based approaches include face-to-face interviews and telephone surveys. Mail-back surveys, hand-delivered questionnaires and Web-based surveys commonly comprise self-selected survey options. The following descriptions of survey approaches are attributed to "Introduction to Survey Design and Delivery" (*NOAA Coastal Services Center, 2007*).

Face-to-Face Interview/Survey

Face-to-face interviews and surveys involve verbal exchange between the interviewer and a single individual. The general distinction between an interview and a survey is question structure.

Interviews generally use open-ended questions to obtain in-depth information about a topic, or qualitative information.

Surveys generally use numeric and categorical responses leading to more general and concise responses, or quantitative information.

Questions in both methods are highly structured so that results can be compiled and compared. If conducted properly, a face-to-face interview results in a generally high response rate and high-quality data. Availability of respondents is another consideration. Face-to-face interviews require respondents to participate immediately or to schedule a time to convene.

Telephone Survey

Telephone surveys are highly effective in generating timely responses. This method is quicker than the face-to-face method. Large numbers of surveys can be acquired in a relatively short time period. As with other verbal techniques, a skilled interviewer is needed to help respondents understand the purpose, time requirements, and survey items. Acquiring a representative sample can be a limiting factor. Partial data are another limitation of telephone surveys, and respondents can terminate an interview at any point by simply hanging up the telephone.

Mail-Back Questionnaire

Mail-back questionnaires provide an opportunity to reach a much broader audience than many other survey methods. A greater portion of the general population possesses a mailing address than a telephone or Internet access. Cost, printing and postage, is relatively inexpensive compared to travel expenses. Though mail-back questionnaires are convenient for respondents, the researcher must wait a longer time for results and take measures to maximize response rates by sending additional surveys and reminder mailings. Current names and addresses are also necessary for adequate participation and response.

Hand-Delivered Questionnaire

This type of questionnaire is essentially the same as other versions except in the way it is administered to respondents. This type of questionnaire is provided to respondents in person, where they are informed of the purpose of the project. Questionnaires are then completed by respondents and returned by mail or picked up at a central location by the surveyor. This method generally receives a greater response rate than the typical mail survey. Hand-delivering the questionnaire presents the opportunity for personal interaction. Respondents may feel more compelled to complete the survey if a positive interaction takes place with the researcher.

Web Survey

Web surveys gather respondent information via the Internet. Information is generally collected by e-mailing respondents a link to an on-line survey. Many research and consulting companies possess their own electronic collection program. On-line surveying can also be independently conducted by means of many Web sites. A few popular Web survey sites are *Zoomerang*, *Insiteful Surveys*, and *Survey Monkey*. These sites, as well as others, offer a variety of free and pay-service options. An advantage of Web surveys is that responses are automatically compiled and outputs are automatically generated. Besides time efficiency, other advantages to Web surveys include reduction in paper and printing costs, and convenience for respondents, who can complete the survey at their convenience.

The greatest detriments to Web surveys are that respondents must possess basic typing and information technology skills, obtain access to a computer with Web access, and, in most cases, have an e-mail account. Additionally, creation of the survey instrument must comply with the constraints of the electronic system used to deliver the instrument.

4.2. ECONOMICS

This section provides background on the economics of mining in the upper Midwest, including common topics and information sources. For illustration, this section reports some economic data for Iron and Ashland Counties, which are currently of interest.

Section 4.1 discusses how individuals perceive and react to projects such as iron mining. The economic issues discussed here are at more of a system level, where individual perceptions matter less than the overall patterns of behavior. However, individual perceptions can strongly influence or even dominate a system, particularly in a small economic system like a rural community. Furthermore, perceptions *of* economic impacts can influence people's opinions and behaviors about a project.

A note on terminology: In this paper, the word "economic" is used in a broad sense, to include commercial activity, intra-firm activity, long-term development, and unpriced effects such as environmental externalities (see below for a definition). The term "commercial activity" refers to buying and selling among individuals, firms, or other entities. It is worth remembering that commercial activity is only part of economic impact.

BACKGROUND

In the United States, mining is now a comparatively small activity, in contrast to the economies of China, Australia, Brazil, and India. Those are the top four iron ore producing countries in the world. Each produces between five times (India) and eighteen times (China) more iron ore tonnage than the U.S. produces (Tuck and Virta 2013).

In the U.S., nearly all iron from ore is produced in the Lake Superior District states of Minnesota (26.2 million metric tons of iron in 2011) and Michigan (7.55 million metric tons in 2011). All other states combined produced just 7 thousand metric tons in 2011(Tuck and Virta 2013).

Approximately 5,000 individuals are employed directly in mining operations in the U.S. (Tuck and Virta 2013). Even in areas with active iron mining operations, mining now accounts for a comparatively small share of local commercial activity (Power 2007).

The following discussion explains general principles that are important for understanding the economic effects of mining in the Upper Midwest, particularly as it is proposed to be undertaken in the Penokee Range.

The first point to understand is that the duration of mine construction and operations influences economic effects. What matters here is how mining duration compares with related economic changes. For an individual mine worker, even a short-lived mine of 10–20 years may be half of a career. On the other hand, compared to the productive life of durable infrastructure such as housing, 10–20 years is relatively short. Furthermore, the most labor-intensive aspect of mining — initial construction — generally lasts only a few years. Long-term economic factors like housing will not adjust as rapidly as short-term employment changes from construction. When assessing the economic effects of mining, these relative time scales must be noted and considered.

Second, the amount of commercial activity generated by mining is limited by the total revenue obtainable from use of the ore body. Mining revenue is the driving force behind mining-related commercial activity. The larger the revenue obtained, the larger the potential commercial activity associated with it. Therefore, the first and most important economic variable in a mining project is likely revenue.[2]

Third, the effects of a mine on the regional economy depend in part on the relative capacity of the region. For instance, a mining operation will need labor, housing, equipment, local transportation, and similar inputs. If the region's ability to supply those inputs is limited, the mine's local impacts will also be limited. Even if local supply capacity is adequate, there may be operational reasons for the mine to source inputs from outside the region, such as price, service, reliability, or contract terms (as in the case of a mining company with multiple locations worldwide).

Similarly, the volatility of a mine's economic impacts also depends on the mine's size relative to the region. Mining operations that constitute a large fraction of the regional economy have a proportionally large negative effect when mine operations end. There is thus a tradeoff between the size of a mine's economic impact on a region and the vulnerability of the region to changes in the mining operation.

Fourth, it is important to distinguish commercial *activity* from economic *development*. Activity is simply the buying and selling associated with a mining operation (or any other business). It includes input purchases by the mining operation including labor (so-called "direct" effects); input purchases by the mine's suppliers ("indirect" effects); and spending by workers in the various affected industries ("induced" effects) (Deller 2004).

Economic development is an increase in the overall productive capacity of a region. It stems from factors like population growth; construction of new infrastructure; establishment of new businesses; increases in educational attainment and workplace skills; and improved human health.

Economic development is a long-term phenomenon. A new business may increase commercial *activity* temporarily without necessarily increasing economic *development*. To affect development, some of the commercial activity of the business must result in investment (in a general sense) in the ongoing productivity of the regional economy. In many mining regions around the world, there exists a tension between short-term economic activity and long-term development (Power 1996; 2005).

Finally, it is also important to distinguish commercial activity from *externalities* associated with the mine (see below for definition and discussion). By their nature, externalities come in a wide variety of types and sizes. Two of particular relevance to mining are human health effects and environmental damage from pollution. Because these effects are not accounted for in any market transaction involving the mining operation, they require additional effort to assess. Note that externalities are first evaluated in physical and biological terms, and are then extended to include estimated value in monetary terms.

---

[2] Depending on the form of business organization for the companies involved in mining, extracted ore may or may not be sold for cash in an arms-length transaction. Wholly-owned vertical operations may receive no revenue from the ore itself.

Common Topics in Mining Economics

This document reflects the following economic topics:

- Context: Locations of proposed mine and neighboring municipalities and counties. Trends in regional population, demographics, employment, personal income, sizes of commercial sectors.
- Project Description: Physical size, duration, phases, etc. Ore body value, gross sales expectations, employment needs, ownership structures, etc.
- Linkages: Local shares of project ownership; equipment and materials supply; and labor supply. Input-Output structure of the local economy; local economic impacts of the project. Major infrastructure requirements such as power and rail. Local capacity constraints on housing, transportation, labor, skilled labor, etc.
- Fiscal Effects: Property, sales, and other taxes expected from the project. Municipal service impacts including water, sewer, and public safety. Zoning and other local regulations and requirements.
- Externalities: Valuation of human health or environmental effects. Changes in the local economy more generally through price or political changes.

It is important to remember that economic methods are tailored to particular purposes. For instance, the purpose of an Environmental Impact Statement (EIS) is to describe impacts of a proposed project in the context of the Wisconsin Environmental Policy Act or Federal Law (WDNR 2013; USEPA 2012b). The act has particular requirements, history, and standards. These differ from other forms of economic analysis, notably Regulatory Economic Impact Analysis, business planning, and academic environmental economics. An existing study or method may not be applicable to an EIS.

To illustrate, Regulatory Economic Impact Analysis of proposed federal administrative rules occurs within a well-developed regulatory framework. In particular, many of the parameter values — like the Value of a Statistical Life — used in those analysis have been researched and negotiated over time among many different federal agencies (USEPA 2010; Sunstein 2013). The values are useful for those agencies in their work of designing efficient and politically acceptable rules, but may not be applicable to the project evaluated in an EIS.

CONTEXT

The economic effects of a mining operation depend on the context of the local economy. Important factors include the location and sizes of nearby communities and commercial activity by sector (Pfeil 2005).

A wide range of data is available to describe a local economy. Useful sources include the U.S. Bureau of Economic Analysis, U.S. Bureau of Labor, and the U.S. Census Bureau (see below for details). The following is an illustration of the kinds of information available, using the Penokee Range as an example.

Example: Penokee Range Communities

The Penokee Range is located in Ashland and Iron Counties in Northern Wisconsin. Both are rural counties with small populations and no micropolitan areas. They had estimated populations of 16,157 and 5,934, respectively, in 2010. Those represent 0.3% and 0.1% of the Wisconsin population, respectively. Both counties have had gradually declining populations since their peaks in the 1940s.[3] The nearest municipalities are given in Table 5.

The Bad River Reservation encompasses much of the watershed downstream from the Penokee Range, beginning roughly 10 miles from the range. Total population on the reservation is approximately 1,800. The majority of people live in one of five "census designated places" (CDP) on the reservation, as shown in Table 6.

TABLE 5. MUNICIPALITIES NEAR THE PENOKEE RANGE

Municipality[a]	Distance[b]	Population[c]
Mellen	5	700
Ashland	25	8,200
Butternut	25	400
Montreal	25	800
Ironwood (MI)	30	5,300
Park Falls	30	2,400
Mercer	40	1,700
Duluth (MN) MSA	95	86,300
Eau Claire MSA	130	67,000
Wausau MSA	130	39,200
Minneapolis — St. Paul (MN) MSA	185	676,200
Green Bay MSA	215	104,900

[a] MSA denotes a municipality that is part of a Metropolitan— or Micropolitan— Statistical Area as defined by the U.S. Census.

[b] Distance Given in miles to the approximate geographic center of the Penokee Range iron deposits. Rounded to the nearest fifth mile.

[c] Population from most recent U.S. Census estimates, usually 2010 or 2011 calendar year. Rounded to the nearest hundred.

TABLE 6. BAD RIVER RESERVATION CENSUS DESIGNATED PLACES

CDP	Distance [a]	Population [b]
Birch Hill	20	300
Frank's Field (Aspen Estates)	20	200
Odanah	25	20
Diaperville (Old Odanah)	30	100
New Odanah	30	500

[a] Distance in miles to the approximate geographic center of the Penokee Range iron deposits. Rounded to the nearest fifth mile.

[b] Population from most recent U.S. Census estimates, usually 2010 or 2011 calendar year. Rounded to the nearest hundred (nearest ten in the case of Odanah).

---

[3] Population figures from U.S. Census Bureau, http://quickfacts.census.gov/qfd/states/55/55003lk.html.

TABLE 7. PERSONAL INCOME BY SECTOR, ASHLAND COUNTY, 2001 AND 2011

Sector	2001	2011
Government and government enterprises	$72,862,000	$100,673,000
Manufacturing	$54,849,000	$60,512,000
Retail trade	$24,620,000	$31,771,000
Construction	$19,072,000	$28,882,000
Other services, except public administration	$12,245,000	$15,044,000
Accommodation and food services	$11,617,000	$12,799,000
Professional, scientific, and technical services	(D)	$10,971,000
Transportation and warehousing	$10,912,000	(D)
Administrative and waste management services	$9,178,000	(D)
Finance and insurance	$8,878,000	$9,921,000
Forestry, fishing, and related activities	$9,937,000	$8,186,000
Farm earnings	$1,272,000	$5,402,000
Information	$3,748,000	$3,553,000
Real estate and rental and leasing	$1,678,000	$1,584,000
Arts, entertainment, and recreation	$1,043,000	$1,222,000
Management of companies and enterprises	(D)	(D)
Mining	(L)	(L)
Other*	$83,197,000	$125,484,000
Total	$325,108,000	$416,004,000

* Primarily utilities, construction, wholesale trade, educational services, health care and social assistance, for which confidentiality restrictions apply.

(D) Not shown to avoid disclosure of confidential information.

(L) Less than $50,000.

Example: Ashland and Iron Counties' Personal Income

Total personal income in 2011 was $521,100,000 and $217,200,000 in Ashland and Iron Counties, respectively. In 2011, income in Ashland County attributable to employment was $416,000,000. Among major industrial sectors, mining has accounted for the smallest share of personal income in Ashland County. Recently, mining personal income has totaled less than $50,000. Table 7 shows personal income by sector for Ashland County for 2001 and 2011.

Similar data could be reported for a range of other variables, including employment and population. Data is available by state, county, census tract, major municipality, and similar groupings.

PROJECT DESCRIPTION

The economic effects of a mining operation obviously depend on the specifics of the proposal. Any evaluation of a particular mining project therefore must include a detailed description of the proposal, which cannot be done until the mining operations plans are well developed.

The following topics are important parts of a project description, among others:

- Project size on the landscape.
- Phases of operation (e.g., planning, construction, operation, closure, monitoring).
- Phase durations.
- Labor needs by phase.
- Equipment needs by phase.

- Labor and equipment sources (including location and business organization).
- Ore body value (point and range estimates; underlying assumptions).
- Ore marketing opportunities (point and range estimates; underlying assumptions).
- Business organization of the project by phase (ownership, vertical integration, partnership agreements, sales agreements, risk pricing, other contracts).
- Non-quantifiable risks to the project plan.

These topics relate to three key issues: the mine's expected gross revenue, property rights governing that revenue, and extent of commercial transactions with the local economy.

LINKAGES

The driving force behind the local economic impact of a mining operation is the total revenue generated by sale of the mine's ore.[4] In the language of economic impact analysis, the ore revenue itself is an "exogenous shock" that drives other effects in the local economy. However, mining revenue alone is not the only issue. In addition, the linkages between the mining operation and other entities in the local economy also matters. Furthermore, linkages among local economic actors also matter.

Deller (2004, pp.2-11) gives an introduction to input-output analysis and linkages. Swenson (2006) give cautions on the misuses of input-output modeling. Aragón and Rud (2013) discuss linkages in the context of gold mining.

Roughly speaking, there are three types of linkage effects considered in an impact analysis, as follows:

1. Direct effects: Spending by the mining operation on materials, equipment, labor, and other other inputs.
2. Indirect effects: Spending by mine suppliers on inputs for their own businesses.
3. Induced effects: Spending by individuals for personal consumption.

To illustrate: the mining operation purchases an item of equipment from a local supplier, the supplier then uses that revenue to purchase additional inputs, including labor, and the supplier's workers then use their income to purchase household goods.

Although thinking about these linkages as separate steps may help to understand how they work, analyzing them that way is practically impossible, because so many businesses buy and sell to one another. To see this, consider the enormous catalog of inputs necessary for even a small equipment vendor. Each item — tractor, light, cable, bolt, etc. — has a commercial history that would have to be traced.

Input-output analysis is the tool used for assessing economic impact linkages. Rather than attempting to model each transaction as steps in a *dynamic* chain, input-output models are based on a *static* table that summarizes the present-day buying and selling patterns among various

---

[4] In the case of a vertically integrated mining—processing operation, the mine's ore may never be "sold" in an open market transaction and thus the price of the ore itself may not be observable (or even defined in a technical sense). However, revenue from the end products to which that ore contributed within the vertically-integrated organization do ultimately yield funds that are spent in furtherance of mining operations.

businesses. By treating those patterns as ratios, one can take the dollar amount of an exogenous shock and simply multiply it against the values in the table.

In other words, an input-output analysis explicitly assumes that the underlying structure of an economy would not change with an exogenous shock. In particular, such a model assumes that no new businesses would be created. It also assumes that there is no "slack" in the system, such as equipment that has been paid for but is not being fully used. That assumption is defensible when the exogenous shock is small relative to the existing local economy, as when one models the opening of a new restaurant in a city. When the shock is large, the assumption is questionable.

One related caution is in order. An input-output model assumes that the exogenous shock connects to the local economy following existing patterns. For instance, if the shock is the aforementioned new restaurant, an input-output model may assume that the restaurant purchases local labor and supplies in the same proportion as existing restaurants do. If the new restaurant in fact buys all of its supplies from out of state the model would be erroneous. A skilled input-output modeler will analyze the particular details of exogenous shock, looking for just such unusual linkages or non-linkages (Swenson 2006). This issue may be important to a mining analysis, because mine supplies and labor can be specialized and may be only available from outside the region.[5]

As was true of the project description section above, an input-output economic impact analysis depends critically on the specific details of a mine proposal. No general analysis can be done, nor would one be helpful.

FISCAL AND PUBLIC SERVICES ISSUES

The input-output economic impact analysis discussed above can also estimate tax revenues associated with an exogenous shock, under the same *ceteris paribus* assumption. However, economic analyses of mining may consider specific fiscal and public service aspects of a mine. As is the theme of this paper, the details of the mining operation are essential to an accurate analysis. The following factors are likely to be relevant:

Fiscal Impacts. Specific payment agreements negotiated between the mining operation and local governments (WDNR 1997a). Non-negotiated requirements on the mining operation, e.g., from zoning law. State taxes or fees related to the project (WDNR1997b; WDOR 2003. Property tax implications of the project, including current payments and reduced land value post extraction. Public Services. Current locations and capacities of public services including schools; hospital and emergency medical services; and police and fire protection. Additional demands anticipated on those services, given the anticipated population changes associated with the mining operation. Capacity of local roads and intersections relative to anticipated additional traffic associated with the mining operation. Changes in rail routes or traffic are anticipated and the effect of such traffic at crossings.

---

[5] It may also be the case that a mine operation chooses to source outside the region for business purposes, such as existing contracts.

EXTERNALITIES

An "externality" occurs when the activity of person *A* has an effect on person *B*, but that effect is *not* negotiated between the two persons in a transaction. Thus, if *A* offers to buy *B*'s house — and *B* agrees —, they have affected one another, but have done so voluntarily by mutual agreement. By contrast, if *A* installs a backyard smelter and pollutes *B*'s adjoining property with no agreement, *A* has imposed a negative externality on *B*. In both cases, the effects are real and important. The difference is the extent to which *B* could influence the effect.

A *technological externality* is an effect caused by physical means, as in the example of pollution generated by one person and experienced by another as reduced health. A *pecuniary externality* is an effect caused by changes in the prices of various other goods, as when purchases by a company raise the market price faced by all other buyers or a political action (e.g., a tax) affects prices.

When a transaction involves the exchange of money, one can use the money as an estimate of the value each person obtains from the transaction. Input-output models; national and regional accounts; and business balance sheets all use money as a convenient way to estimate value. Externalities do not involve exchanges of money, so it cannot be used to make an estimate.

To emphasize, the absence of money exchange does not imply that an effect is imaginary or unimportant. Instead it poses a measurement problem. That problem must be solved in two steps:

1. Assess the *size* of the effect. Assess how much pollution results, how widely dispersed it is and how many people are affected,
2. Estimate people's *valuation* of the effect at that size.

The estimate can be done either by asking people directly (e.g., with a survey) or by observing some market transaction that is related to the effect (e.g., sale prices of land in the area).

Since technological externalities are physical effects, they will be evaluated first in physical or biological terms. Evaluating them as economic issues means taking the second step of estimating the value of the physical effects in monetary terms. That is useful because it allows one to compare unpriced externalities with priced commercial effects. One might find, for instance, that the commercial activity of a proposal totals $100 million, and the external health and environmental harms are valued at $10 million. One's opinion of that project would be different than if the values were reversed.

Pecuniary externalities are also relevant to mining economics. By changing the relative prices of goods and services in a region, a mine affects other parts of the local economy. These effects are harder to analyze and less often included when evaluating projects. Fortenbery and Deller (2006) discuss such effects in the context of bioenergy processing facilities.

To repeat the theme of this paper, valuation of externalities depends on the specifics of a mining operation. There is a large body of literature applying valuation methods to particular topics. It is unlikely that any of those results will apply directly to a mining operation in Northern Wisconsin.

DATA SOURCES

U.S. Bureau of Labor Statistics

The Bureau of Labor Statistics[6] (BLS) is:

"…the principal Federal agency responsible for measuring labor market activity, working conditions, and price changes in the economy. Its mission is to collect, analyze, and disseminate essential economic information to support public and private decision-making. As an independent statistical agency, BLS serves its diverse user communities by providing products and services that are objective, timely, accurate, and relevant." [7]

BLS provides data on employment; unemployment; and pay and benefits. Data is available at national, state, and county levels. Some series (e.g., unemployment rates) are available for metropolitan and small labor market areas. Data are compiled annually for all series. Some series are also available quarterly or monthly.

U.S. Bureau of Economic Analysis

The Bureau of Economic Analysism[8] (BEA) gathers "economic accounts" data at the national, regional, industrial, and international levels.[9]

BEA data includes Gross Domestic Product (nationally and by state), personal income, and regional input-output tables used in impact analyses. Data are available at the national, state, county, and metropolitan levels. All series are available annually. Many are available quarterly or semi-annually.

U.S. Census Bureau

The Census Bureau[10] offers so much data that no short summary would be helpful. Here are a few notable items:

Industry statistics, including financial reports, sales, establishments, and establishment formation–dissolution. http://www.census.gov/econ/industry/.

Demographics, including population, migration, housing, school enrollment, and well-being. http://www.census.gov/people/.

Data access and mapping tools, including interactive population maps, county-level "quick stats", business dynamics tables, and worker characteristics maps. http://www.census.gov/main/www/access.html.

U.S. Geological Survey, National Minerals Information Center

The Minerals Information Center provides data "on the worldwide supply of, demand for, and flow of minerals and materials."[11] Data are available by commodity, country, and state. Information on iron ore includes annual commodities summaries, industry surveys, prices, a report on challenges facing the North American iron ore industry, and the outlook for the world iron ore industry through 2017.

---

[6] http://www.bls.gov.

[7] Quotation from http://www.bls.gov/bls/infohome.htm (retrieved 2013–06–21).

[8] http://www.bea.gov.

[9] Quotation from http://www.bea.gov/about/Econaccts.htm (retrieved 2013–06–21).

[10] http://www.census.gov.

11 Quotation from http://minerals.usgs.gov/minerals/pubs/index.html (retrieved 2013–06–21).

5. WATER QUALITY MONITORING

5.1. OBJECTIVES

The first step in the design of a monitoring program is to specify objectives (Dixon and Chiswell 1996, Maher et al. 1994, Ward and Loftis 1986). The goals of mine-related monitoring are determined by permitting and compliance requirements as well as by the nature of the mining, including the characteristics of deposits, amount and disposal of waste rock, processing activities at the site, construction of facilities and roads, etc. Monitoring objectives for a given mine will depend on the specific conditions at that mine and will be determined during the permitting process as the ore body is investigated, the project facilities are planned, and baseline conditions are evaluated. Three objectives of monitoring that pertain to mining are: 1) determination of baseline conditions; 2) compliance with water quality standards; and 3) evaluation of changes in water quality.

Monitoring is most effective if sample locations used to determine baseline conditions are maintained throughout the life of the mine; this improves the precision of comparisons between time periods and of trend estimates. Some sample locations necessary for characterizing baseline conditions may not be needed for later monitoring, but continued sampling at some of the sample locations is advantageous because of the increased precision of comparisons. Because compliance monitoring may necessitate sample stations located above and below the mine and above and below discharge points (USEPA 2003a), knowledge of the location of mining facilities is important in planning sampling during the baseline sampling period. Information acquired during baseline monitoring will be used to develop a monitoring plan required as part of the National Pollution Discharge Elimination System (NPDES) permit process (USEPA 2003a).

5.2. MONITORING DESIGN

Two major components of surface water monitoring design are selecting sample locations and determining sampling frequency (Dixon and Chiswell 1996, Khalil and Ouarda 2009, Maher et al. 1994, many others). These two design factors can interact, so that sampling frequency may vary among locations (e.g., McDonald 2003).

Sampling locations for mine monitoring are determined to a large extent by the location and nature of the mine and by permitting requirements. Detecting and evaluating changes in water quality related to a mine or to any human activity is difficult because natural variation is always present and may be difficult to separate from human-caused changes (Skalski and McKenzie 1982, Smith 2002). Since at least the 1970's it has been recognized that comparisons with reference conditions are an important feature of environmental monitoring (Eberhardt 1976, Green 1979). Standard monitoring designs typically include samples from unimpacted sites as well as samples from the time period before any change or impact is expected (e.g., Skalski and McKenzie 1982). Thus, sample stations for mine monitoring should be located above and below the mine on any streams or rivers that flow through the mine site, as well as above and below discharge points; they should be located at upstream and downstream sites on at least one stream not expected to be directly impacted by the mine (i.e., reference watershed); on lakes near the mine; and monitoring at all sites should begin before the mine begins operation (USEPA 2003a). Sample locations in lakes are often located near inflow, either surface water or seepage, and at the deepest part of the lake. In lakes that stratify, samples are usually obtained from several depths.

Comparisons with reference conditions can control for multiple sources of variability. For instance, there may be differences in water chemistry between upstream and downstream sites on a stream that are caused by differences in surface runoff or groundwater inflow independent of the mine. Samples from the period before the mine begins operation allow estimation of such differences, so that upstream-downstream differences after the mine is operating can then be compared with those that existed previously. Similarly, having data from unaffected streams or lakes can control for changes in environmental conditions, thus preventing the effects of an environmental change, such as a drought or extreme rainfall, from being confused with an effect of a mine.

Sample frequency is closely related to sample size. An increased rate of sampling will result in a larger sample size in the same time period, but at an increased cost. Sample size is traditionally determined from considerations of desired precision or confidence interval width (Ward et al. 1979). In a monitoring situation, sample size will automatically increase over time, so the precision of annual means may be used to determine sample frequency (Loftis and Ward 1980a). Statistical determination of sample size requires an estimate of the variability of each constituent. More intensive sampling during the period of baseline monitoring may be necessary to obtain estimates of variability that can then be used to determine appropriate sample size for further monitoring. For constituents that exhibit less variation, less frequent sampling will be adequate. Samples taken within a short time frame may be autocorrelated, which complicates sample size estimation and data analysis (Loftis and Ward 1980b). In addition, concentrations of some constituents are strongly related to flow, so that regular, fixed-interval sampling may miss important variation in concentration (Robertson and Roerish 1999, Harmel et al. 2003, Harmel et al. 2006, Horowitz 2013). Concentrations of constituents that are associated with sediments tend to increase greatly in high flow conditions, while concentrations of dissolved constituents may decrease through dilution during high flow (Horowitz 2013, Harmel et al. 2006). Under low flow conditions, water quality is dominated by point sources and groundwater inflow, while during high flow, water quality tends to be dominated by nonpoint sources (Horowitz 2013). These considerations suggest that sampling frequencies may vary for different constituents: substances adsorbed to sediments and carried in runoff may require more frequent sampling during storm or other high flow events, and may be more efficiently carried out using automated sampling (Harmel et al. 2003).

Mine monitoring plans often involve a combination of fixed, regular sampling dates supplemented by samples under high flow conditions (USEPA 2003a). As an example, the British Columbia Ministry of the Environment recommends a baseline monitoring sampling schedule of 'monthly sampling with additional weekly sampling (i.e., 5 samples in 30 days) during periods of maximum hydrograph fluctuation' (MOE 2012).

5.3. ANALYSIS

Just as monitoring objectives determine the design of a monitoring program, they also inform the analysis of data collected. Two common analytical objectives of mine monitoring are to compare water quality data with established environmental standards or with reference or baseline conditions. The methods used for comparison may vary, as may the criteria for determining when regulatory action occurs. It is generally best to outline analysis methods and regulatory criteria during the design of the monitoring program, even if some details cannot be specified until data are available (for instance, if a statistical test is to be carried out, the form of the test may depend on the observed distribution of the data, or on the observed correlation among observations). If analyses will include comparisons with regulatory standards, the meaning of an exceedance of a standard should be clarified. For point-source discharges in Wisconsin, this is specified to some extent in NR 106.

Estimates should be accompanied by confidence intervals to provide information on precision (Gardner and Altman 1986, Hoenig and Heisey 2001). For comparison with a standard, it may be enough to compute a mean (or other estimate) and associated confidence interval, although plots of observations versus time may suggest trends or step changes. If hypothesis tests are used they should be formulated carefully to ensure that the most important errors are minimized (McBride et al. 1993). The standard null hypothesis of no difference may be inappropriate when comparing to a baseline because in this case there may be only a small probability of detecting biologically important changes. It is well known that failing to reject a null hypothesis is not the same as accepting the null hypothesis: failure to reject a null hypothesis may occur when the precision of the estimate is low and the data are consistent with a wide range of values, including some that may be biologically important (Parkhurst 2001, McBride 2002). Formal comparisons with reference conditions are best carried out through equivalence tests (Parkhust 2001, Manly 2004). A brief discussion of this technical issue is provided in Appendix B.

5.4. GROUNDWATER MONITORING

Many of the issues involved in groundwater monitoring are similar to those already discussed for surface water monitoring, but there are some important differences. Determination of baseline conditions may be more difficult for groundwater because the nature of aquifers and groundwater flow patterns is often not known. Determining baseline conditions may require placement of many groundwater monitoring wells, not all of which may be needed once flow patterns are understood. Mines may affect groundwater levels both through mine construction that disrupts baseline flow and through pumping to remove water from the mine or for processing (USEPA 2003a). Groundwater wells are thus used both for sampling water quality and assessing groundwater level and flow rates.

It is usually necessary to establish a network of groundwater wells around the proposed mine site to determine baseline groundwater flow directions, rates, and water quality; some wells may be eliminated once flow patterns have been delineated (MOE 2012). If more than one aquifer may potentially be affected by mining activities, all of the aquifers should be sampled (USEPA 2003a). Standard groundwater well configurations have been proposed for waste disposal sites or known contaminated sites that may be useful for mines as well (Maqsood et al. 2004, Meyer et al. 1994). In general, a minimum of one upgradient well and 4 or 5 downgradient wells will be required for continued monitoring, but often more wells are appropriate (Maqsood et al. 2004).

Groundwater data collected during the baseline monitoring period are used in groundwater modeling for the mine site (USEPA 2003a). Groundwater models are usually necessary to develop a site water balance for managing runoff, discharges, and flow rates. Such models are also useful in designing better groundwater well monitoring networks (Maqsood 2004).

Sample frequency considerations for groundwater monitoring are similar to those for surface water monitoring and are affected by the variability of constituent concentrations and water levels. Schot and Pieber (2012) found that spatial variability in groundwater composition was greater than temporal variability, but it is not clear how general this conclusion is. They also found that nutrient concentrations were more variable than concentrations of macroions including sulfate, carbonates, and metals (Schot and Pieber 2012). Zhou (1996) used standard statistical sample size analyses to determine that a sampling frequency of once every two months was adequate for estimating mean water levels, but that more frequent sampling was necessary to estimate periodic fluctuations in level. Most groundwater monitoring programs appear to sample quarterly, but some involve less frequent sampling (Johnson et al. 1996).

Many discussions of analysis methods for groundwater monitoring are directed at hazardous waste sites, landfills, and other sites involving some form of waste disposal (USEPA 2009, Gibbons 1996, Davis and McNichols 1999). Such sites are regulated under the Resource Conservation and Recovery Act (RCRA), but solid wastes from mining were exempted from this act. Subsequent rules have modified this so that some mine wastes, such as waste solvents, follow the same regulations as other industrial wastes (USEPA 1994, USEPA 2003a). Analytical methods for these wastes are described in the EPA Guidance document on groundwater monitoring at RCRA facilities (USEPA 2009). Methods described in the current document for surface water analysis may be appropriate for constituents not covered by special regulations that apply to RCRA facilities.

6. LABORATORY METHODS

Many of the environmental monitoring requirements, including what approved methods and limits may apply and what laboratory certification is necessary, can be found in the approved Wisconsin Natural Resources State Statutes and Administrative Codes. Table 8 lists many of these Chapters and their titles.

All mining waste or leachate from the wastes needs to meet the standards that apply to groundwater, surface water and wetlands (Wis Statute Chapter 295). The approved methods applicable to the Clean Water Act (CWA) are tabled in the current revision of the Federal Register, 40 CFR, part 136. Approved technologies for the environmental analysis of non-drinking water samples in Wisconsin can be found in Chapter NR219 of the Wis Admin Code. Please note that for wastewater discharge samples, the SW846 methods will not apply in the next revision of NR 219 and are not acceptable to the EPA. Technologies for environmental analysis of solid matrices are listed in appendices of NR 149. If parameters are not listed by any of the programs or included in the regulations (e.g., methylmercury), those methods should be reviewed by department staff for applicability and sensitivity.

TABLE 8. WISCONSIN NATURAL RESOURCES STATE STATUTES AND ADMINISTRATIVE CODES RELEVANT TO TACONITE MINING

Code reference	Title
Wis. Statute Chapter 295 Subchapter III	FERROUS METALLIC MINING
Wis. Statute Chapter 285	AIR POLLUTION
Wis Admin Code Chapter NR 102	WATER QUALITY STANDARDS FOR WISCONSIN SURFACE WATERS
Chapter NR 105	SURFACE WATER QUALITY CRITERIA AND SECONDARY VALUES FOR TOXIC SUBSTANCES
Chapter NR 106	PROCEDURES FOR CALCULATING WATER QUALITY BASED EFFLUENT LIMITATIONS FOR POINT SOURCE DISCHARGES TO SURFACE WATERS
Chapter NR 140	GROUNDWATER QUALITY
Chapter NR 149	LABORATORY CERTIFICATION AND REGISTRATION
Chapter NR 219	ANALYTICAL TEST METHODS AND PROCEDURES
Chapter NR 809	SAFE DRINKING WATER
Chapter NR 299	WATER QUALITY CERTIFICATION

As discussed in several chapters, including Wis. Stats. 295.64 (2) and 299.11, the laboratory tests are to be performed by a laboratory certified or registered for the matrices and parameters being analyzed. Exceptions for certain tests are noted in these chapters. Asbestos and radiological analysis shall be performed by the State Laboratory of Hygiene or at a laboratory certified or approved by the Department of Agriculture, Trade and Consumer Protection (DATCP) or deemed acceptable by the DNR Drinking and Groundwater program. DATCP also certifies laboratories that test drinking water samples for bacteria. The American Industrial Hygiene Laboratory Accreditation Program (AIHA-LAP) certifies industrial hygiene laboratories for testing methods of air samples for EPA regulated pollutants. For geochemical assays pertaining to whole rock analysis (i.e., waste characterization, discussed below) and particle size determination is not discussed in detail here. Laboratories experienced with the specialized preparation and analytical techniques of ore samples should be used (ASTM E1915).

Both field and laboratory QA/QC are strongly recommended to support defensibility. Extensive and detailed requirements for laboratory QC procedures are typically specified in the methods. If not specified by the method, the type and frequency of field QC samples should be determined prior to collecting samples for a specific project. Quality control samples are prepared in the field and at the laboratories to monitor the bias and precision of the sample collection and analysis procedures. Laboratory protocols for method detection limit studies and confirmation procedures are required as written in Chapter NR149 of the Wis Admin Code. The accuracy and precision criteria are indicated in the analytical method or method reference, including the applicability of laboratory performance based control limits. Consideration for the sensitivity of the technique chosen must meet the specified data quality objectives wherever possible.

A brief explanation of many of the relevant analytical techniques is including in Appendix C.

6.1. TOXICITY ANALYSIS

WET, whole effluent toxicity testing is commonly performed on wastewater effluent, though in the case of taconite mining operations WET testing on stormwater discharges, from waste rock storage areas, for example, is appropriate. Both acute toxicity (lethality, as quantified by the LC_{50}) and chronic toxicity (inhibition, as quantified by the IC_{25}) are assessed. Organisms such as water fleas, fat head minnows and algae are used to measure lethal and sub-lethal effects after exposure to different concentrations of the samples for specified lengths of times. The approved method for WI waters is *"State of Wisconsin Aquatic Life Toxicity Testing Methods Manual"* (Methods Manual), 2nd Edition, November 2004.

WET has the major advantage of being able to identify the potential for harm to downstream aquatic life without needing to identify the source of toxicity. WET testing may be particularly useful for routine monitoring of mining operations, because the composition of waste water may vary with ore composition, etc. If significant toxicity is revealed by WET, wastewater can subsequently be systematically evaluated to identify the source of toxicity.

FIGURE 15. AN ARRAY OF HUMIDITY CELLS IN THE RINSING PHASE (TOP) AND AN INDIVIDUAL HUMIDITY CELL CONTAINING GREENSTONE ROCK (BOTTOM). CREDIT: KIM LAPAKKO, MINNESOTA DNR.

6.2. WASTE CHARACTERIZATION

ASTM D 5477-07 (or most recent approved version) is used to determine acid mine drainage (potential). Humidity cells are set up with samples of waste rock and flushed with water to create a laboratory-weathering experiment designed to enhance the mass release of acidity/alkalinity, metals, and other pertinent analytes from a sample of solid material. This is done by providing conditions conducive to sample oxidation and then leaching the sample with a fixed volume aqueous leach. The ratio of leach volume to sample mass ranges from 0.5:1 to 1:1 depending upon the efficiency of sample wetting and amount of effluent required for chemical analyses. There are two options in the method, and these only differ by how oxygen is supplied to samples. The effluent produced is sampled weekly and characterized for dissolved weathering products. The analysis on the effluent typically includes pH, eH (redox potential), conductivity, alkalinity, cations/anions and trace metals. The specific list of cations/anions and metals may need to be reviewed once a laboratory has been determined. A laboratory that has experience meeting the requirements of the ASTM method is needed, as the set up for a specific project must take into account the specific materials, time duration as well as a variety of effects including particle size (Lapakko and Antonson 2012). A typical humidity cell apparatus is shown in Figure 15.

The duration of the test should be determined based on the situation at a specific site. First, it is necessary to clearly define the objectives of the test. Second, at regular intervals (for example yearly) assess whether the objectives have been met based on the initial solid phase characterization and the drainage quality data generated to date.

While a standard test duration cannot be prescribed, humidity cell testing often requires several years to fully evaluate AMD potential of mine waste. A major concern historically, therefore, is that a mine waste will be categorized as “not acid producing” based on a relatively short period of dissolution testing. Samples have been tested that produced circumneutral drainage for periods of roughly 2, 5, 8, and 14 years then produced acidic drainage (K. Lappako, MN Department of Natural Resources, personal communication with B. Baker-Muhich). The drainage quality from these samples could have been described as “stable” for many years, but the ultimate drainage quality could not have been extrapolated from those periods of stability. Thus, waste rock characterization should not be viewed only as an initial testing procedure, but rather as an ongoing process that can serve as an “early warning” system for potential pollution problems throughout the life of a mine.

7. ANNOTATED BIBLIOGRAPHY

Adams, J.L. 1983. Changes in streamflow following construction of a taconite tailing basin in northeast Minnesota. Pages 211-216 *in* D.H. Graves, editor. Proceedings of the 1983 symposium on surface mining, hydrology, sedimentology, and reclamation. University of Kentucky,Lexington, Kentucky.

Changes in downstream hydrology (stream flows and lake surface elevations) were evaluated following construction of a tailings basin which consumed a large portion of a headwaters area. Both high flows and annual average flows were reduced, as were lake elevations.

Adams, J.L. 1994. The water balance of abandoned mine pits. Minnesota Ground Water Association 13(1):4-9.

This paper describes an approach for evaluating the hydrologic budget of abandoned mine pits as they fill with water. Topics relevant to mine reclamation are discussed, such as channel design, placement, and construction if it is determined there will be surface outflow and the final water elevation.

Adams, J.L. 1998. Hydrologic changes affected by Inland Steel's in-pit tailings disposal proposal.

This study evaluated groundwater flow through a mine pit which was to be used for tailings disposal. Another pit lake located downgradient from the pit in question served as a municipal water source for Virginia, MN; there were concerns that the in-pit tailings operation could negatively impact drinking water quality. The importance of reducing infiltration by increasing evapotranspiration (i.e., revegetating) from the tailings surface is emphasized.

Adams, J.L., R.T. Leibfried, and E.S. Herr. 2004. East Range hydrology project. Minnesota Department of Natural Resources, Division of Lands and Minerals/Division of Waters, Grand Rapids, Minnesota.

This project predicted watershed-scale hydrologic changes associated with the closure and reclamation of a large taconite mining site in Minnesota (Cliff-Erie Mining Company). Time to fill, outflow locations and discharge rates, and channel designs are presented for several pits, and impacts on other local hydrologic features are evaluated.

Applied Ecological Services. 2008. Black River Falls mine restoration. Accessed online at http://www.appliedeco.com/projects/Black%20River%20Falls%20-%20Jackson%20Co%20Mine%20Restoration.pdf.

Aragón, F. M. and J. P. Rud. 2013. Natural resources and local communities: Evidence from a Peruvian gold mine. American Economic Journal: Economic Policy, 5(2):1–25.

Aragón and Rud look for evidence of local economic benefits caused by gold mining at Yanacocha, Peru, one of the largest gold mines in the world. They find that "...at least in the short run, the expansion of the mine has a positive impact on the living standards of the local population, and that the effects are driven mainly by the mine's backward linkages." They also note that, since 2000, the demand for local inputs increased significantly, driven by the growth of gold production and the implementation of a corporate policy directed at increasing local employment and supply linkages. The main limitation of the paper is its study duration. The paper did not examine "long-run phenomena such as specialization, technological progress, or agglomeration economies."

ASTM International (2007) Designation: D5744 – 07 Standard Test Method for Laboratory Weathering of Solid Materials Using a Humidity Cell, www.astm.org.

ASTM International (2011) ASTM E1915 Revision/Edition 11. Standard Test Method for Analysis of Metal Bearing Ores and Related Materials for Carbon, Sulfur and Acid-Base Characteristics. www.astm.org.

ATSDR (Agency for Toxic Substances and Disease Registry). 1999. Toxicological Profile for Mercury. U.S. Department of Health and Human Services, ATSDR.

ATSDR (Agency for Toxic Substances and Disease Registry). 2001. Toxicological Profile for Asbestos. U.S. Department of Health and Human Services, ATSDR.

ATSDR (Agency for Toxic Substances and Disease Registry). 2003. Toxicological Profile for Selenium. U.S. Department of Health and Human Services, ATSDR.

The ATSDR toxicological profile succinctly characterizes the toxicological and adverse health effects information for the hazardous substance described here. Each peer-reviewed profile identifies and reviews the key literature that describes a hazardous substance's toxicological properties. Other pertinent literature is also presented, but is described in less detail than the key studies.

ATSDR (Agency for Toxic Substances and Disease Registry). 2008. Health Concerns Related to Asbestos in Stockpiled Demolition Debris, former Solvay coke facility, Milwaukee, Wisconsin, EPA facility ID: WIN000508215. Prepared by Robert Thiboldeaux for U.S. Department of Health and Human Services, Public Health Service Agency for Toxic Substances and Disease Registry Division of Health Assessment and Consultation. Atlanta, Georgia.

This report is an ATSDR health consultation. From the report: "An ATSDR health consultation is a verbal or written response from ATSDR to a specific request for information about health risks related to a specific site, a chemical release, or the presence of hazardous material. In order to prevent or mitigate exposures, a consultation may lead to specific actions, such as restricting use of or replacing water supplies; intensifying environmental sampling; restricting site access; or removing the contaminated material." This consultation includes of summary of public health-relevant regulations and guidelines regarding asbestos-containing material.

Austin, A. and J. Deniseger. 1985. Periphyton community changes along a heavy metals gradient in a long narrow lake. Environmental and Experimental Botany. 25(1):41-52.

This study examined the impact of mining on a periphyton in a lake on Vancouver Is. Diatom diversity was low in the part of the lake where the discharge stream entered. Diversity increased down shore away from the mine. Sensitive taxa were of low abundance near the mine but their numbers increased down the lake.

Aylesworth, R. J., D. R. Becker., and M. A. Kilgore. 2008. Benchmarking Minnesota's environmental review and permitting processes for forestry and mining industries: A comparative assessment. Staff Paper 195, Department of Forest Resources, College of Food, Agricultural and Natural Resource Sciences, University of Minnesota, St. Paul, Minnesota.

This paper evaluates Minnesota's environmental review and permitting processes by comparing them with the processes of states with comparable forestry and mining industries. The paper contains valuable lessons about the environmental assessment process itself. Those lessons are summarized on pp. iii–vi. The paper evaluates review process variation, uncertainty, public involvement strategies, effects of public involvement on the process, and assessment of cumulative impacts, among other topics. The underlying lessons appears to be that environmental review is complicated, variable, and subject to wide discretion.

Bavin, T. and Berndt, M. (2008). Sources and fate of sulfate in NE Minnesota watersheds: A minerals coordinating committee progress report (DNR Reclamation Report 6176). Minnesota Department of Natural Resources, Division of Lands and Minerals.

This document discusses the sources and impacts of sulfate ions in watersheds down-gradient of iron mines in Minnesota. The sources include iron mine waste-rock piles, precipitation, scrubbers on coal-burning power plants, and wastewater treatment plants. The impacts are on wild rice, increased methylation of mercury, and lake eutrophication. The St. Louis River and its tributaries are discussed in detail. Based on data from 2007 and before, the study concludes that sulfate controls are complex, and that there is a positive correlation between dissolved chloride and mercury in mining-impacted streams. Sulfate concentrations were considerably higher in mining impacted tributaries than in non-mining tributaries. Mercury (total and methylmercury) concentrations did not appear to be correlated with sulfate in this study.

Benner, B.R. 2008. Bench scale tests to separate mercury from wet-scrubber solids from taconite plants. Minnesota Department of Natural Resources. 26 p.

Minnesota has initiated the goal of reducing mercury emissions from taconite processing by 75%. A series of projects, jointly funded by public and private interests, have studied techniques to reduce these mercury emissions. The website: http://www.dnr.state.mn.us/lands_minerals/dnr_hg_research.html "contains links to studies conducted by (or for) the DNR - Division of Lands and Minerals, Reclamation Section. These reports detail on-going efforts to control mercury concentrations in taconite stack emissions." This particular study summarizes work at five northeastern Minnesota taconite mines, and concludes that some mercury reduction can be achieved by thickening and cycloning the "minus 10 mesh" dust fractions.

Benson S.A., J. Nasah, C. Thumbi, S. Patwardhan, L. Yarbrough, H. Feilen, and S.F. Korom. 2012a. Evaluation of Scrubber Additives and Carbon Injection to Increase Mercury Capture. Minnesota Department of Natural Resources, St. Paul, MN. 67 p.

This study comes from the University of North Dakota, and summarizes field tests of proprietary mercury sorbent formulations at the Minntac Line 3 facility. This is a data-rich report, but is best viewed as a work-in-progress in terms of mercury reduction.

Benson S.A., N. Lentz, S. Patwarhan, J. Nasah, C. Thumbi, and H. Feilen. 2012b. Evaluation of a Low Corrosion Method to Increase Mercury Oxidation and Scrubber Capture. Minnesota Department of Natural Resources. St. Paul, Minnesota: 66 p.

This study comes from the University of North Dakota, and summarizes ongoing work from Benson et al. 2012, using ESORB-HG-11, a proprietary brominated powdered activated carbon that showed promise during the 2012a study.

Berger, R. L. and J. C. Hsu. 1996. Bioequivalence trials, intersection-union tests and equivalence confidence sets. Statistical Science 11:283-319.

This paper clarifies the relationship between confidence intervals and the two one-sided tests (TOST) procedure for testing for bioequivalence proposed by Schuirman (1987). It also extends bioequivalence tests to problems with more than one parameter.

Berndt, M.E. 2003. Mercury and Mining in Minnesota: Minerals Coordinating Committee Final Report. Minnesota Department of Natural Resources, Division of Lands and Minerals.

This report summarizes mercury sources and cycling in Minnesota. It concludes that the largest input of mercury to lakes in NE Minnesota is atmospheric deposition and the mercury is globally sourced. Mercury is released into the atmosphere when iron ore is heated during the processing of taconite pellets, which adds to the global mercury load, but not necessarily to the amount in local lakes and fish. Methylation of mercury takes place in freshly deposited sediments on lake bottoms. There is a large variation in the amount of mercury in taconite – from 1 kg to 17 kg of Hg per million long tons of ore across the Minnesota Iron Range. Berndt M.E. 2008. On the measurement of stack emissions at taconite processing plants - a progress report submitted to MPCA. Minnesota Department of Natural Resources, St. Paul, MN. 23 p.

This report is from the MN Pollution Control Agency, and reviews progress to date with emphasis on the brominated stack additives described by Benson et al. 2012a,b.

Berndt, M. E. and T. K. Bavin. 2009. Sulfate and Mercury Chemistry of the St. Louis River in Northeastern Minnesota: Final Report to the Minerals Coordinating Committee. Minnesota Dept. of Natural Resources. Division of Lands and Minerals. St. Paul MN. December 15, 2009.

Berndt, M. E. and T. K. Bavin. 2012a. "Methylmercury and dissolved organic carbon relationships in a wetland-rich watershed impacted by elevated sulfate from mining." Environmental Pollution 161: 321-327.

Berndt, M. E. and T. K. Bavin. 2012b. On the Cycling of Sulfur and Mercury in the St. Louis River Watershed, Northeastern Minnesota .An Environmental and Natural Trust Fund Final Report. Minnesota Department of Natural Resources. St. Paul, MN. August 15, 2012

Berndt, M.E. and W.C. Brice. 2008. The origins of public concern with taconite and human health: Reserve Mining and the asbestos case. Regulatory Toxicology and Pharmacology 52:S31-S39.

This paper summarizes the controversy surrounding Reserve Mining in the 1970s, largely focused on possible asbestos fibers in mine tailings, that ultimately led to a switch from disposing of mine tailings in Lake Superior to land-based disposal. The emphasis of this document is on the legal aspects of the case.

Berndt, M., and Engesser, J., 2005, Mercury transport in taconite processing facilities: (I) release and capture during induration: Minnesota Department of Natural Resources Division of Lands and Minerals, Iron Ore Cooperative Research Final Report, 60 p. http://files.dnr.state.mn.us/lands_minerals/reclamation/BerndtandEngesser2005a.pdf

This report details the release of mercury from magnetite when it is heated and converted to hematite during the manufacturing of taconite pellets. Four taconite facilities in Minnesota were studied to assess ways to decrease mercury in stack emissions. Volatilized Hg^{o} is not effectively caught by scrubbers, but capture of oxidized mercury is increased in the presence of chlorine.

Besch, W.K., M. Ricard, and R. Cantin. 1972. Benthic diatoms as indicators of mining pollution in the Northwest Miramichi River System, New Brunswick, Canada. Internationale Revue der gesamten Hydrobiologie. 57(1):39-74.

Besser, J.M., T.J. Canfield, and T.W. La Point. 1993. Bioaccumulation of organic and inorganic selenium in a laboratory food chain. Environmental Toxicology and Chemistry 12:57-72.

Bioaccumulation of selenium was measured in controlled cultures of algae, daphnids, and bluegill, using radiolabelled selenium (^{75}Se). Selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), and selenomethionine were tested separately, and these species were found to concentrate differently, with the organic compound accumulating most strongly. Bioconcentration factors for each organism and species are presented. Algae and daphnids accumulated selenite more strongly than selenite, but fish accumulated both similarly. While food-chain uptake is the primary exposure pathway for bluegill, direct uptake of organic selenium compounds may also be significant.

Besser, J.M., W.G. Brumbaugh, T.W. May, and C.J. Schmitt. 2007. Biomonitoring of lead, zinc, and cadmium in streams draining lead-mining and non-mining areas, southeast Missouri, USA. Environmental Monitoring and Assessment. 129:227-241.

In this study the accumulation of metals in periphyton, invertebrates and fish was compared between streams sites below mines and reference sites. Biota from sites below mines had much higher metal concentrations.

Bjornerud, M., Knudsen, A., and Trotter, J., 2012, Geochemical, mineralogical and structural characterization of the Tyler Formation and Ironwood Iron Formation, Gogebic Range, Wisconsin: http://www.lic.wisc.edu/glifwc/penokee/bjornerud_2012/Bjornerud_Geology_Report_Jan2013.pdf

This paper provides an overview of the stratigraphy, structure, mineralogy, and geochemistry of the rocks in and adjacent to the Ironwood Formation. Chemical and mineralogical analyses were performed on rocks from surface outcrops and from a drill core stored at the Wisconsin Geological and Natural History Survey. This is the only drill core that is publicly available for this part of the stratigraphy. The chemistry and mineralogy of the pyritic layer from the Yale Member of the Ironwood Formation is described in detail. The report discusses the significant acid generating and negligible neutralizing capacity of the rocks, as well as their relatively high phosphorus content. The report also provides estimates of the volume of waste rock that would be generated by an open-pit mine in the Penokee Range.

Brix, K.V., J.S. Volosin, W.J. Adams, R.J. Reash, R.G. Carlton, and D.O. McIntyre. 2001. Effects of sulfate on the acute toxicity of selenite to freshwater organisms. Environmental Toxicology and Chemistry 20(5):1037-1045.

This study demonstrates the dependence of selenate toxicity on sulfate concentrations. Acute selenate toxicity decreases with increasing sulfate. A statistical relationship is used to propose a sulfate-dependent water-quality criterion for selenate.

Bruns, D.A. 2005. Macroinvertebrate response to land cover, habitat, and water chemistry in a mining-impacted river ecosystem: A GIS watershed analysis. Aquatic Sciences. 67:403-423.

This study compared the benthic macroinvertebrate communities below mining sites and compared them with sites without mining. At sites below mines the functional group collectors-gatherers was greatly reduced compared with the reference sites. EPT richness was especially reduced. Stream sites below mines had greater sedimentation in the streams compared with the reference sites.

Cade, R. S. 2011. Estimating equivalence with quantile regression. Ecological Applications 21:281-289.

Cade generalizes the concept of equivalence tests from means to arbitrary quantiles of a distribution. This provides a method for handling data with heterogeneous variances. His paper also includes examples of equivalence testing using environmental data.

Cannon, W.F., Woodruff, L.G., Nicholson, S.W., Hedgeman, C.A., 1996, Bedrock geologic map of the Ashland and northern part of the Ironwood 30'x60' quadrangles, Wisconsin and Michigan, scale: 1:100,000, one sheet. http://tin.er.usgs.gov/catalog/cite-view.php?cite=398

This map shows all of the bedrock units and the structure of the Penokee Range in Wisconsin east of 91° west latitude. It shows most of the detail of the Ironwood Formation displayed on the map of Cannon et al., 2008, but extends further east. The legend has a thorough and concise summary of the geology, geologic history, and economic geology of all the Precambrian bedrock units in the region. This is a very important map of the area.

Cannon, W.F., LaBerge, G.L., Klasner, J.S., and Schulz, K.J. 2008, The Gogebic Iron Range -- A sample of the northern margin of the Penokean Fold and Thrust Belt: USGS Professional Paper 1730. http://pubs.usgs.gov/pp/pp1730/

This paper describes the bedrock stratigraphy and structural geology and of the Penokee Range in detail. It summarizes the mining history of the Range and briefly discusses the economic geology and potential future taconite mining in the Ironwood Formation. There is a lot of detail on the structural geology and deformation of the rocks during the Penokean Orogeny of the Paleoproterozoic. The map that accompanies the paper as Plate 1 is the most detailed published map of the Ironwood Formation and adjacent units in Wisconsin. The map shows the western end of the Penokee Iron Range – from Jackson Lake in Bayfield County east to the area of Tyler Forks Rivers in Iron County, Wisconsin. This USGS Professional Paper is one of the most important documents on the geology of the Penokee-Gogebic Range because it is a recent summary of all aspects of the geology, including the economics of the taconite in the Range.

Chapman P.M., W.J. Adams, M.L. Brooks, C.G. Delos, S.N. Luoma, W.A. Maher, H.M. Ohlendorf, T.S. Presser, D.P. Shaw. 2009. Ecological assessment of selenium in the aquatic environment:

Summary of a SETAC Pellston Workshop. Society of Environmental Toxicology and Chemistry, Pensacola, Florida.

This document summarizes a SETAC workshop held in 2009, and summarizes the state of the science on selenium contamination. It emphasizes that diet (i.e., bioaccumulation) is the primary exposure pathway for invertebrates and vertebrates, and as such, traditional methods of predicting toxicity (i.e., chronic and acute toxicity testing) are not adequate. Speciation influences fate and transport and toxicity, and the food web present at a particular location also determines bioaccumulation factors. Thus, a single dissolved water quality value is inappropriate for predicting toxicity, and site-specific risk assessments are required to a greater extent than with many other contaminants. Fish and bird eggs are the most reliable way of assessing selenium toxicity.

Clayton, L., and Attig, J.W. 1990. Geology of Sauk County, Wisconsin: Wisconsin Geological and Natural History Survey, Information Circular 67, 68 p. http://wisconsingeologicalsurvey.org/pdfs/IC67.pdf

This document describes the stratigraphy and geologic history of Sauk County, including the Precambrian rocks in the Baraboo Hills that contain iron ore in the Freedom Formation.

Colombo, A.F. and H.D. Jacobs. 1976. Beneficiation of nonmagnetic taconites by selective flocculation-cationic flotation. U.S. Bureau of Mines, Report of Investigations 8180, Twin Cities, Washington, D.C.

Colombo, A.F. H.D. Jacobs, and D.M. Hopstock. 1978. Beneficiation of western Mesabi range oxidized taconite. U.S. Bureau of Mines, Report of Investigation 8325, Washington, D.C.

Condie, L.W. 1983. Review of published studies of orally administered asbestos. Environmental Health Perspectives 53:3-9.

This is a review of 11 published studies on the carcinogenic risk associated with ingestion of asbestos. Based on these studies, there appeared to be little evidence of such risk.

Conley, J.M., D.H. Funk, and D.B. Buchwalter. 2009. Selenium bioaccumulation and maternal transfer in the mayfly *Centroptilum triangulifer* in a life-cycle, perifphyton-biofilm trophic assay. Environmental Science and Technology 43:7952-7957.

Selenium bioaccumulation in periphyton biofilms and mayflies was assessed using radiolabelled selenium (^{75}Se). The periphyton bioconcentrated selenium by a factor of greater than 1000 after 7-9 days of exposure, while the mayflies biomagnified selenium by another factor of 2.2 and transferred approximately half of their body burden to their eggs. A diet of high selenium periphyton negatively impacted mayfly reproduction.

Daniels, D.L., and Snyder, S.L. 2002. Wisconsin aeromagnetic and gravity maps and data: a web site for distribution of data: U.S. Geological Survey, Open-File Report 02-493. http://pubs.usgs.gov/of/2002/of02-493/HTML/WI_hi-res_mag_image.htm

This digital aeromagnetic map shows the magnetic intensity of rocks in Wisconsin. The magnetic intensity is controlled by the amount of iron in the rocks, so the iron formations are readily apparent owing to their greater magnetic susceptibility in comparison to adjacent rock units.

Davies, M.P. 2011. Filtered dry stacked tailings – the fundamentals. *in* Proceedings of Tailings and Mine Waste 2011, Vancouver, British Columbia.

Davies, M.P. and S. Rice. 2004. An alternative to conventional tailings management – "dry stack" filtered tailings. *in* Proceedings of the Eighth International Conference on Tailings and Mine Waste, Fort Collins, Colorado.

Both Davies (2011) and Davies and Rice (2004) present dry stacking of tailings as an alternative to conventional tailings management (e.g., storage ponds and impoundments). In this method, the tailing slurry undergoes vacuum filtration, leaving a dry waste material that is physically transported to a waste storage facility. While costs are higher than conventional systems, the dry storage of tailings decreases the risk of environmental contamination.

Davis, C. B. and R. J. McNichols. 1999. Simultaneous nonparametric prediction limits. Technometrics 41:89-101.

The Davis and McNichols paper describes a statistical method used in monitoring of constituents with unusual distributions, or, especially with large numbers of values below detection limits. This approach is frequently used in groundwater monitoring at hazardous waste sites.

Deller, S. C. 2004. Wisconsin and the agricultural economy. Staff Paper 471, University of Wisconsin- Madison Department of Agricultural & Applied Economics. Available: http://www.aae.wisc.edu/pubs/ sps/pdf/stpap471.pdf.

This paper evaluates the importance of agriculture to the Wisconsin economy. It relies on the construction and use of a regional economic modeling approach called input-output (IO) analysis, also called multiplier analysis. The paper begins with a detailed but readable overview of the basics of input-output modeling (pp. 2–7). The discussion begins by noting that, "[a]s a descriptive tool, IO analysis represents a method for expressing the economy as a series of accounting transactions within and between the producing and consuming sectors. As an analytical tool, IO analysis expresses the economy as an interaction between the supply and demand for commodities. Given these interpretations, the IO model may be used to assess the impacts of alternative scenarios on the region's economy." The paper applies such a model to Wisconsin agriculture on pp. 12–15.

Deniseger, J. A. Austin, and W.P. Lucey. 1986. Periphyton communities in a pristine mountain stream above and below metal mining operations. Freshwater Biology. 16:209-218.

Periphyton communities were reduced in diversity below the mine site compared with above the mine. The major community impacted was soft algae. The Chlorophyta Mougeotia spp. and Ulothrix subtilissima were virtually absent during the summer below the mine. While diatoms were common above and below the mine, the diversity and species evenness were reduced below the mine.

Dixon, W. and B. Chiswell. 1996. Review of aquatic monitoring program design. Water Resources 30: 1935-1948.

This paper reviews monitoring program design and provides a useful summary of the literature before 1996. The authors discuss regulatory monitoring as well as more general monitoring programs. The paper includes coverage of variables to measure, statistical

analysis methods, and principles of design, including spatial distribution of samples and sampling frequency. Most of the paper is devoted to surface water quality monitoring, but it includes a section on groundwater monitoring as well.

Drost, J.J. and W.M. Mahan. 1973. Effects of thermal treatments upon concetratability of a nonmagnetic iron ore. U.S. Bureau of Mines, Report of Investigations 7797, Washington, D.C.

Durham, R.W. and T. Pang. 1975. Asbestos fibers in Lake Superior. Pages 5-13 *In* Barabas, Silvio, editor. Water Quality Parameters. American Society for Testing and Materials, ASTM STP 573, Baltimore, Maryland.

This paper describes the results of a survey of Lake Superior designed to assess the geographic extent of the occurrence of mineral fibers in the water, originating from tailings being disposed of in Silver Bay. It was shown that fiber concentrations are elevated in the western arm of the lake, but were not being transported to the eastern arm or north to Thunder Bay.

Dutton, C.E., 1983, Lithology and geologic setting of Lower Proterozoic iron-formations in part of northern Wisconsin, U.S. Geological Survey, Open-File Report 84-76. http://pubs.usgs.gov/of/1984/0076/report.pdf

This report describes the geology of the poorly exposed iron ranges in northeastern Wisconsin including the Turtle and Manitowish Ranges, and the Vieux Desert and Conover Districts. Although these iron formations are mostly buried under glacial deposits, their structure and lithology are known from magnetic surveys and exploration drill cores, which are summarized in this report.

Eberhardt, L, L. 1976. Quantitative ecology and impact assessment. Journal of Environmental Management 4:27-70.

In a general discussion of impact assessment, Eberhardt presents the Before-After-Control-Impact (BACI) design before it was given that name. Most of his examples are from wildlife ecology and fisheries biology, but his discussion is clear and wide-ranging.

Edwards, K.J., Bond, P.L., Druschel, G.K., McGuire, M.M., Hamers, R.J., Bandrield, J.F., 2000, Geochemical and biological aspects of sulfide mineral dissolution: lessons from Iron Mountain, California: Chemical Geology, v. 169, p. 383- 397. http://www.uvm.edu/~gdrusche/papers/Edwards%20et%20al.,%202000%20CG%20-%20Iron%20Mountain.pdf

The Richmond sulfide ore body at Iron Mountain, California is the site of some of the most metal-rich and acidic mine drainage in the world so a lot of research has been conducted on the generation of acid mine drainage at the site. This paper provides a concise review of the chemical, microbial, and kinetic aspects of sulfide mineral dissolution and the generation of acid mine drainage. The importance of microbial influences on acid drainage is covered in detail – something that was not addressed in most earlier papers.

Engstrom, D. R. and Swain, 1997. E. B. Recent declines in atmospheric mercury deposition in the upper Midwest. Environ. Sci. Tech. 31, 960-967.

Erickson, K. 1994. A new species of trouble: explorations in disaster, trauma, and community. W.W. Norton & Company, New York.

In this book, sociologist Kai Erikson visited communities around the United States that experienced man-made disasters. He discovered that the communities shared a common thread of dread and helplessness. He concludes that this is a new type of trauma and urges society to do more to protect people from it.

Evers, D.C., J.G. Wiener, N. Basu, R.A. Bodaly and H.A. Morrison. 2011. Mercury in the Great Lakes region. Ecotoxicology 20(7). Special Issue

Ferrari, J.R., T.R. Lookingbill, B. McCormick, P.A. Townsend, and K.N. Eshleman. 2009. Surface mining and reclamation effects on flood response of watersheds in the central Appalachian Plateau region. Water Resources Research 45:W04407.

This study compared flood response characteristic of reclaimed surface coal mines in the central Appalachian Plateau with unmined sites. While vegetation at each type of site is practically identical, it was determined that flood magnitude is significantly greater at reclaimed mine sites. The authors suggest that reclamation is not successful in returning an area to pre-mining hydrological conditions.

Fitzgerald, W. F. 1989. Atmospheric and Oceanic Cycling of Mercury. Chemical Oceanography Series. J. P. Riley and R. Chester. Academic Press, 10, 151-186.

Fortenbery, R. T. and S. Deller. 2006. Understanding community impacts: a tool for evaluating externalities from local bio-fuels production. Technical Report 505, University of Wisconsin-Madison Department of Agricultural & Applied Economics. Available: http://www.aae.wisc.edu/renk/library/Biofuel_ production_isjext.pdf.

This paper presents an economic analysis tool for use by local policy makers in public investment options for bio-refining plants. The tool helps determine how extensive the community benefits will be as a result of subsidizing a plant. The tool was developed for University Extension educators to use in their community development role. The tool is based on input-output modeling. The paper includes a brief overview of that modeling technique.

Foster, P.L. 1982. Species associations and metal contents of algae from rivers polluted by heavy metals. Freshwater Biology. 12:17-39.

The periphyton community in this study was mostly soft algae. The periphyton community in rivers in the non-mining area was dominated by Spirogyra and Mougeotia while sites in the mining area were dominated by Microspora. Algal metal concentrations were several orders of magnitude higher than ambient levels.

Frommer, D.W. and P.A. Wasson. 1963. Lake Superior iron resources: further metallurgical evaluation of Mesabi Range nonmagnetic taconites (reduction roasting and magnetic separation). U.S. Bureau of Mines, Report of Investigations 6104), Washington, D.C.

Frommer, D.W., P.A. Wasson, and D.L. Veith. 1973. Flotation of Marquette Range nonmagnetic taconite using innovative procedures). U.S. Bureau of Mines, Report of Investigations 7826, Washington, D.C.

Galbreath, K.C. 2005. Mercury Vaporization Characteristics of Taconite Pellets. Minnesota Department of Natural Resources. 24 p.

This study comes from the University of North Dakota, and describes baseline bench studies from 2005 that quantitate the amount and form of mercury released when green taconite pellets are heat-cured.

Gardner, M. J. and D. G. Altman. 1986. Confidence intervals rather than P values: Estimation rather than hypothesis testing. British Medical Journal 292:746-750.

Although Gardner and Altman write for a biomedical audience, they present a careful discussion of problems with the interpretation of P values and the advantages of using confidence intervals to summarize results.

Genter, R.B., D.S. Cherry, E.P. Smith, and J. Cairns Jr., 1987. Algal-periphyton population and community changes from zinc stress in stream mesocosms. Hydrobiologia. 53:261-275.

This study used mesocosms to determine the effect of increasing zinc concentrations on periphyton. As the zinc concentration increased the community shifted from diatoms to green or blue-green algae.

Gibbons, R. D. 1996. Some conceptual and statistical issues in analysis of groundwater monitoring data. Environmetrics 7:185-199.

Gibbons is one of the major figures in developing statistical methods for analysis of groundwater monitoring data from hazardous waste sites. This paper gives a summary of the statistical issues involved, including multiple comparisons, parametric and nonparametric procedures, and methods for dealing with observations below the limit of detection.

Gilmour, C. C., E. A. Henry, and R. Mitchell. 1992. Sulfate stimulation of mercury methylation in freshwater sediments. Environmental Science and Technology 1092, 26, 2281-2287.

This report is frequently cited as the seminal work linking sulfate pollution into surface waters with the microbial formation of methyl mercury.

GLIFWC (Great Lakes Indian Fish & Wildlife Commission). 2011. Iron Mining in the Lake Superior Basin (Project Report 11-1). GLIFWC Environmental Section, Odanah, WI.

This report was commissioned to review potential environmental impacts of taconite mining in northern Wisconsin. It is useful as a general introduction to local geology, taconite mining technology, and environmental issues.

Grant, U.S. 1903. Preliminary report on the lead and zinc deposits of southwestern Wisconsin. Wisconsin Geological and Natural History Survey, Economic Series no. 5, Bulletin no. 9, Madison, Wisconsin.

Overview of lead and zinc mining in the Wisconsin portion of the Upper Mississippi Valley district (Grant, Lafayette, and Iowa counties), including a bibliography of prior publications on the topic. Iron sulfides (primarily marcasite and pyrite) were present in many of the ores mined, and processed where sufficiently abundant.

Green, R.E. and A.F. Colombo. 1984. Dispersion-selective flocculation-desliming characteristics of oxidized taconites. U.S. Bureau of Mines, Report of Investigations 8867, Washington, D.C.

Green, R. H. 1979. Sampling design and statistical methods for environmental biologists. Wiley.

Green's book gives one of the first discussions of designs to assess environmental impact. Although better designs are now available, his book provides clear discussion of the issues and interesting examples.

Grigal, D. F. 2003. Mercury sequestration in forests and peatlands: A review. Journal of Environmental Quality 32 393-405.

Hanna, B. 2011. Neutral mine drainage water-quality impacts from a former taconite mine. In *Tailings and mine waste '10*. Taylor & Francis, London.

This paper, presented at the 14th annual Tailings and Mine Waste Conference in Fort Collins, CO, describes a study carried out by Itasca Denver, Inc. at the site of the former Cliffs Erie mine in Hoyt Lakes, MN. A suite of geochemical characterization techniques were applied to samples of stockpiled waste rock, *in situ* rock, groundwater, and pore water from waste rock piles. Sulfate, hardness, alkalinity, iron, manganese, and aluminum were identified as potential constituents of interest. The proposed mechanism for this suite of constituents is pyrite oxidation followed by neutralization by the magnesium-rich siderite ($Ca_{0.03}Mg_{0.20}Fe_{0.73}Mn_{0.04}CO_3$) present at this site.

Hanna, B. and K. Lapakko. 2012. Waste rock sulfate release rates at a former taconite mine, laboratory and field-scale studies. In *Proceedings of the 9th International Conference on Acid Rock Drainage (ICARD).* Ottawa, ON.

This study follows up Hanna (2011) with an estimate of sulfate mass loading to pit lakes and a stream draining several pit watersheds at the site of the former Cliffs Erie Mine (Hoyt Lakes, MN). Sulfate release in the field ranged from 8 to 28 grams of sulfate per kilogram of iron sulfide per year. Scaling factors for laboratory/field comparisons are presented.

Harmel, R. D., K. W. King, B. E. Haggard, D. G. Wren, and J. M. Sheridan. 2006. Practical guidance for discharge and water quality data collection on small watersheds. Transactions of the American Society of Agricultural and Biological Engineers 49:937-948.

Like the 2003 Harmel et al. paper (see below), this paper is concerned with storm water sampling. It provides a good discussion of the advantages and disadvantages of both baseflow and storm water sampling, and of the design issues associated with automated sampling.

Harmel, R. D., K. W. King, and R. M. Slade. 2003. Automated storm water sampling on small watersheds. Applied Engineering in Agriculture 19:667-674.

The Harmel et al. paper applies primarily to storm water sampling but gives a good discussion of the implications of using time- or flow-based sampling intervals.

Hawley, J.E., and Beaven, A.P., 1934, Mineralogy and genesis of the Mayville Iron Ore, Wisconsin: The American Mineralogist, v. 19, no. 11, p. 493-514. http://www.minsocam.org/ammin/AM19/AM19_493.pdf

This paper describes the mineralogy of the goethite-hematite oolitic iron ores of the Phanerozoic-type iron deposits of Mayville District in southern Wisconsin.

Heising, L.F. 1963. Open-pit mining, milling, and costs, Groveland mine, the Hanna Mining Co., Dickinson County, Mich. U.S. Bureau of Mines, Information Circular 8181, Washington, D.C.

This is a report on operations at an early open-pit taconite mine utilizing flotation techniques. A history of the site, a detailed description is provided of all stages of the mining process, and economic and labor figures are provided.

Herr, E.S., and J.M. Gleason. 2007. Central Mesabi iron range hydrology study. Minnesota Department of Natural Resources, Division of Lands and Minerals/Division of Waters.

This study formulates water balances for seven natural ore pits that have been abandoned for more than 20 years in order to determine whether water levels had reached equilibrium or would continue to rise. Future ranges in water elevations are modeled, and pit outflow locations are identified. A water balance model is also developed for growing taconite pit complexes based on anticipated future mining activity. A potential for future diversion of Lake Superior water (a violation of the Great Lakes Compact) is identified.

Hoenig, J. M. and D. M. Heisey. 2001. The abuse of power: The pervasive fallacy of power calculations for data analysis. The American Statistician 55:1-6.

The paper by Hoenig and Heisey demonstrates the inadequacy of using post hoc power analysis to interpret results of non-significant null hypothesis tests. They point out that both confidence intervals and equivalence tests are more useful for interpreting data in such cases.

Hornbeck, J.W., M.B. Adams, E.S. Corbett, E.S. Verry, and J.A. Lynch. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology 150:323-344.

Hornbeck, J.W., C.W. Martin, R.S. Pierce, F.H. Bormann, G.E. Likens, and J.S. Eaton.1986. Clearcutting northern hardwoods: effects on hydrologic and nutrient ion budgets. Forest Science 32(3):667-686.

The initial phase of mine pit development involves the removal of native vegetation, typically forest in northern Wisconsin. These two studies by Hornbeck et al. examine the effect of clearcutting on the hydrology and biogeochemistry of impacted sites. Both water yield and nutrient ion export increases dramatically following clearcutting. In a managed forest setting (in contrast with a mine site) these effects are relatively short-lived when forest regrowth is allowed to proceed.

Horowitz, A. J. 2013. A review of selected inorganic surface water quality-monitoring practices: Are we really measuring what we think, and if so, are we doing it right? Environmental Science and Technology 47:2471-2486.

Horowitz reviews issues associated with sample collection, sampling frequency, and preservation and analysis of samples, primarily in non-regulatory situations.

Howard, J.H., III, 1977, Geochemistry of selenium: formation of ferroselite and selenium behavior in the vicinity of oxidizing sulfide and uranium deposits: Geochimica et Cosmochimica Acta, v. 41, no. 11, p. 1665-1678. http://www.sciencedirect.com/science/article/pii/0016703777901764

This is an important foundational paper that describes the basic geochemical behavior of selenium. Selenium can substitute for sulfur and be bonded to iron in pyrite. The stability of selenium phases is shown in Eh-pH diagrams in this paper. The behavior of selenium ions in aqueous solutions is also discussed.

Hrabik, TR and CJ Watras. 2002. Recent declines in mercury concentration in a freshwater fishery: isolating the effects of de-acidification and decreased atmospheric mercury deposition in Little Rock Lake. Sci. Tot. Environ. 297:229-237.

Huber, N.K., 1959, Some aspects of the Ironwood Iron-Formation of Michigan and Wisconsin: Economic Geology, v. 54, p. 82-118.

This paper is a detailed description of the stratigraphy and mineralogy of the different rock types within the Ironwood Formation, including those containing siderite, magnetite and hematite, pyrite, and other miscellaneous rocks types. The distribution and origin of the units is also covered. Much of the content is summarized, with some additional information, in more recent publications by Schmidt 1980, and Cannon et al 2008.

Irving, R. D. and C.R. Van Hise, C. R. 1892. The Penokee iron-bearing series of Michigan and Wisconsin. U.S. Geological Survey, Lake Superior Division, Washington, D.C.

Comprehensive report on a geological field survey of the Penokee Series conducted between 1884 and 1886. Includes a history of prior explorations (with bibliography). At the time this survey was conducted mining had already begun along the Penokee range, and many of the mines were utilized in this survey. Output and ore quality of major mines is also summarized in Chapter 1.

James, H.L., 1951, Iron formation and associated rocks in the Iron River District, Michigan: Geological Society of America Bulletin, v. 62, no. 3, p. 251- 266. Abstract is available here: http://gsabulletin.gsapubs.org/content/62/3/251.short

This paper describes the lithology of the iron formation of the Iron River District in Michigan, which extends a short distance into Wisconsin. This Lake Superior-type iron formation is made up of iron oxides, chert, siderite, and pyrite. The origin of the rocks and the conditions under which they formed is discussed in detail.

Jamieson, H.E., 2012, Geochemistry and mineralogy of solid mine waste: essential knowledge for predicting environmental impact: Elements, v. 7, p. 381-386. http://171.66.125.216/content/7/6/381.short

This is an important up-to-date summary paper on the acid-generating and -neutralizing capacity of waste rocks from mines. It discusses the importance of the ratio of sulfide minerals to carbonate minerals in waste-rock piles.

Johnson, N.W. and B.F. Beck. 2012. Sulfur and carbon controls on methyl mercury in St. Louis River Estuary sediment: Phase II. University of Minnesota Duluth, Department of Civil Engineering and Water Resources Science Graduate Program.

This research report was funded within Minnesota’s ongoing efforts to understand environmental issues associated with taconite mining. Mining is mentioned but not discussed; instead this work focuses on the sulfate and methyl mercury chemistry of a major stream and Lake Superior tributary known to be affected by mining in northeastern Minnesota. The background section reviews biotic, abiotic, and organic carbon interactions within the sediment chemistry of this complex topic. The experimental section employs

laboratory experiments using sediment cores from the St. Louis River estuary, with a focus on sediment pore water, and a comparison of the local formation of methyl mercury compared to introductions from upstream deposition.

Johnson, V. M., R. C. Tuckfield, M. N. Ridley, and R. A. Anderson. 1996. Reducing the sampling frequency of groundwater monitoring wells. Environmental Science and Technology 30:355-358.

This paper provides a simple method for determining the frequency of groundwater sampling that can be applied in regulatory situations where the emphasis is on estimating trends in contaminant concentrations.

Jones, D.G., 1978, Geology of the iron formation and associated rocks of the Jackson County Iron Mine, Jackson County, Wisconsin: Institute on Lake Superior Geology, 24th Annual Meeting Proceedings Volume, p. 19. http://www.d.umn.edu/prc/lakesuperiorgeology/Volumes/ILSG_24_1978_pt1_Milwaukee.CV.pdf

This brief paper describes the geology of the iron ore deposit and the surrounding rocks in Jackson County, Wisconsin.

Jones, P.M. 2002. Characterization of ground-water flow between the Canisteo mine pit and surrounding aquifers, Mesabi iron range, Minnesota. U.S. Geological Survey, (Water-Resources Investigations Report 02-4198, Mounds View, Minnesota.

This USGS report describes a comprehensive study of the groundwater connections between the Canisteo mine pit (a complex of abandoned natural ore pits) and surrounding aquifers. A water budget is presented for the pit, and pit outflow it simulated over time. Once the pit is full, surface outflow will occur at three locations.

Khalil, B. and T. B. M. J. Ouarda. 2009. Statistical approaches used to assess and redesign surface water-quality-monitoring networks. Journal of Environmental Monitoring 11:1915-1929.

Khalil and Ouarda provide a recent review of water quality monitoring methods, including definition of objectives, selection of variables, design principles, such as selecting sampling locations and sampling frequencies, and methods of statistical analysis. Although not targeted at assessing effects of industrial operations or management activities, it gives a useful overview of monitoring approaches.

Klofstad, C. A. 2004. Interview. Pages 359-363 *in* K. Kempf-Leonard, editor. Encyclopedia of social measurement. Academic Press, San Diego.

This chapter provides a succinct summary of the pros and cons of applying various interview techniques to the measurement of social phenomenon. It discusses personal interviews, focus groups and questionnaires.

Kohn, C.F. and R.E. Sprecht. 1958. The mining of taconite, Lake Superior iron mining district. Geographical Review 48(4):528-539.

This is an excellent contemporary account of early taconite mining operations. The history (through 1958) of taconite exploitation is discussed, as are processing methods. Early mines in Minnesota and Michigan are discussed. It is also noted that at the time this paper was

written, the Ashland Mining Company was contemplating constructing a large-scale taconite concentration plant near Butternut.

Langmuir, D., 1997, Aqueous environmental geochemistry, Prentice Hall, 600 p.

This is a graduate-level textbook on aqueous geochemistry that covers the reactions involved in acid rock drainage and models for predicting acid drainage based on mineralogy and aqueous geochemisty.

Lapakko, K.A and Antonson D.A. 2012 Duluth Complex Rock Dissolution and Mitigation Techniques Research Summary. Minnesota Department of Natural Resources, St. Paul, Minnesota.

Leino, R. L. and J. H. McCormick. 1993. "Responses of juvenile largemouth bass to different pH and aluminum levels at overwintering temperatures: effects on gill morphology, electrolyte balance, scale calcium, liver glycogen, and depot fat." Canadian Journal of Zoology 71: 531-43.

Lemly, A.D. and G.J. Smith. 1987. Aquatic cycling of selenium: Implications for fish and wildlife. U.S. Fish and Wildlife Service, Fish and Wildlife Leaflet 12, Washington, D.C.

The majority of selenium in the environment is either absorbed or ingested by organisms, or bound to particulate matter. Selenate (Se^{6+}) undergoes reduction to selenite (Se^{4+}), which binds to clay and organic particles and settles. In the sediment, oxidation and methylation make selenium available for biotic uptake. Rooted plants, benthic invertebrates, and bottom-feeding fish take up available sediment selenium. Because significant bioaccumulation can occur, toxic effects on biota are possible even when aquatic concentrations are low. Reproductive failure within higher trophic levels (fish, birds) is the most likely result of elevated selenium.

Lemly, A.D. 2004. Aquatic selenium pollution is a global environmental safety issue. Ecotoxicology and Environmental Safety 59:44-56.

Selenium pollution is widespread and due to a number of human activities (agriculture, industry, etc.). The potential effects of selenium on aquatic ecosystems is more significant that many other aquatic pollutants, and thus it should be included in monitoring programs. Due to its long life in the environment, it is difficult to reverse selenium pollution; prevention is key.

Likens, G.E., R F. Wright, J N. Galloway and T. Butler. 1979. Acid Rain. *Scientific American*. 241 (4): 43-51.

Loftis, J. C. and R. C. Ward. 1980a. Cost-effective selection of sampling frequencies for regulatory water quality monitoring. Environment International 3:297-302.

This paper is similar to the companion paper published in Water Resources Bulletin, except that it adds explicit budgetary constraints.

Maher, W. A., P. W. Cullen, and R. H. Norris. 1994. Framework for designing an sampling programs. Environmental Monitoring and Assessment 30: 139-162.

Maher et al. give a general overview of steps that must be taken in designing an environmental sampling program. Although it does not give many specific recommendations, it does provide a useful guide to the design process.

Malmqvist, B. and P. Hoffsten. 1999. Influence of drainage from old mine deposits on benthic macroinvertebrate communities in central Sweden. Water Research. 33:2415-2423.

This study done in Sweden compared the macroinvertebrate communities at sites below old mine sites and compared them with reference sites. Sites below the mines had reductions in taxonomic richness for total macroinvertebrates, mayflies, stoneflies, and combined EPT but not for that of Trichoptera nor total abundance or biomass.

Manly B. F. J. 2004. One-sided tests of bioequivalence with nonnormal distributions and unequal variances. Journal of Agricultural, Biological, and Environmental Statistics 9:270-283.

Maqsood, I., G. H. Huang, and Y. F. Huang. 2004. A groundwater monitoring design through site characterization, numerical simulation and statistical analysis – A North American case study. Journal of Environmental Informatics 3: 1-23.

The Maqsood et al. paper presents an integrated approach to characterize groundwater at a site, develop a simulation model of contaminant movement, and design a network of groundwater monitoring wells. They present three different methods of locating wells, with advantages and disadvantages of each. They apply their method to a site contaminated with petroleum.

Marsden, R. 1978. Iron ore reserves of Wisconsin: A minerals availability system report. *in* Proceedings of the American Institute of Mining Engineers 51st Annual Meeting, Duluth, MN.

This report provides an overview of known reserves in the state. At the time of writing, the Jackson County Iron mine was in operation; information is provided on this facility. Extensive information is provided on the Gogebic Range, by far the largest unexploited reserve of taconite ore. This paper defines the upper and lower ore zones of the Ironwood Formation and presents the widely cited figures on the tonnage of economic ore in the Range (3.711 billion metric tons). Information is also provided on several smaller taconite deposits: Tilden Mound, Agenda, Butternut, and Pine Lake.

McBride, G. B. 2002. Statistical methods helping and hindering environmental science and management. Journal of Agricultural, Biological, and Environmental Statistics 7:300-305.

McBride points out weaknesses of null hypothesis significance tests and of p-value summaries without confidence intervals. He briefly discusses the use of equivalence tests as an alternative.

McBride, G. B., J. C. Loftis, and N. C. Adkins. 1993. What do significance tests really tell us about the environment? Environmental Management 17:423-432.

This paper gives general background on significance tests used in environmental monitoring. It points out problems in interpretation of the tests and situations where other forms of analysis, such as equivalence tests, may be more appropriate. It includes an example involving groundwater monitoring.

McCormick, J. H. and K. M. Jensen. 1992. Osmoregulatory Failure and Death of First-Year Largemouth Bass (Micropterus salmoides) Exposed to Low pH and Elevated Aluminum, at Low Temperature in Soft Water*. Canadian Journal of Fisheries and Aquatic Sciences* 49: 1189-1197

McDonald, M.G. and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. Chapter A-1 *in* U.S. Geological Survey Techniques of Water-Resources Investigations, book 6. U.S. Geological Survey, Reston, Virginia.

This book chapter provides technical documentation for MODFLOW, a groundwater flow model developed by the USGS which is commonly applied to predict the impact of mining operations on groundwater hydrology.

McDonald, T. L. 2003. Review of environmental monitoring methods: Survey designs. Environmental Monitoring and Assessment 85:277-292.

McDonald reviews survey designs for long-term environmental monitoring. Although much of his paper has little to do with water quality monitoring, his coverage of many designs that incorporate schedules involving staggered sampling times at different locations is useful.

McFarland, B.H., B.H. Hill, and W.T. Willingham. 1997. Abnormal Fragilaria spp. (Bacillariophyceae) in streams impacted by mine drainage. Journal of Freshwater Ecology. 12(1):141-149.

This study found that the diatom genus Fragilaria exhibited elevated rates of morphological abnormalities at sites below mines and mine tailings piles. The percent of abnormalities ranged from 0.2% to 12% with the greater abnormalities tending to occur at sites with the highest dissolved metal concentrations in the water. This was especially true for elevated concentrations of zinc and iron. The pH values in these systems were 7.7-8.5.

McNeal, J.M., and L.S.Balistrieri. 1989. Geochemistry and occurrence of selenium: an overview. Pages 1–13 *in* L.W. Jacobs, editor. Selenium in agriculture and the environment. Soil Science Society of America Special Publication 23.

This paper describes the naturally occurring dissolved ions of selenium and how their geochemical behavior is largely controlled by the pH and redox conditions in the environment.

MDEQ (Michigan Department of Environmental Quality). 2009. An assessment of environmental selenium levels around Empire and Tilden mines, Marquette County, Michigan. MDEQ, MI/DEQ/WB-09/038, Lansing, Michigan.

This report presents the result of water, sediment, and fish tissue selenium sampling in the vicinity of the Empire and Tilden taconite mines. While the acute criterion was only exceeded in a water rock pile seep, the chronic criterion was exceeded at many sampling sites. Sediment concentrations in a downstream lake were in excess of recommended maximum levels for protection of wildlife. Fish tissues were also in exceedence of EPA guidelines.

MDEQ (Michigan Department of Environmental Quality) and Cliffs Natural Resources. 2010. Update on selenium projects at Tilden and Empire Mines, MI. http://www.michigan.gov/documents/deq/wrd-npdes-EmpireTilden-Vol1_364698_7.pdf

This is a concise public newsletter about the water quality in Goose Lake and other water bodies near the Empire and Tilden iron mines in Michigan. Phosphorus and selenium sources and hazards are discussed, as well as on-going efforts to understand and control selenium contamination.

MDH (Minnesota Department of Health). 2007. Mesothelioma in Northeastern Minnesota and Two Occupational Cohorts: 2007 Update. MDH, Center for Occupational Health and Safety, Chronic Disease and Environmental Epidemiology Section.

Stated purpose of report: "This document provides a brief summary and update of the rates and characteristics of mesothelioma cases in three populations: (1) Northeast (NE) Minnesota (comprised of the seven counties: Aitkin, Carlton, Cook, Itasca, Koochiching, Lake, St. Louis; (2) a cohort of approximately 72,000 iron miners ever employed in taconite mining in NE Minnesota in or prior to 1983; and (3) a cohort of approximately 5,200 workers employed at the Conwed Corporation (Wood Conversion Co.) plant in NE Minnesota anytime between 1958 and 1974."

MDNRE (Michigan Department of Natural Resources and Environment). 2010. 2009 selenium monitoring conducted by selenium monitoring work group around Empire and Tilden mines, Marquette County, Michigan. MDNRE, MI/DNRE/WB-10/021, Lansing, Michigan.

This follow up study to the 2009 report includes additional monitoring data in the vicinity of the Empire and Tilden mines, confirming elevated selenium in these systems. Additional control site sampling was also done to verify that background selenium concentrations are low in this area. Finally, sampling was performed at historical mine sites in the region; sediment selenium concentrations were found to be very high at one site (out of four sampled).

MPCA (Minnesota Pollution Control Agency). 2011. The Sulfate Standard to Protect Wild Rice Study Protocol (WQ-S6-42B). MPCA.

This document was cited in the context of what Minnesota has done to protect their wild rice resource. From the Introduction: "This document identifies key information to enhance understanding of the effects of sulfate on wild rice, and options for obtaining data that address those needs. The goal is to obtain information that would allow the Minnesota Pollution Control Agency (MPCA) to further evaluate and, if appropriate, revise Minnesota's sulfate water quality standard for the protection of wild rice."

MPCA (Minnesota Pollution Control Agency). 2012. National Pollutant Discharge Elimination System (NPDES)/State Disposal System (SDS) Permit MN0068241: Essar Steel Minnesota LLC.

MPCA (Minnesota Pollution Control Agency). 2013. Minnesota's Wild Rice Sulfate Standard. Compilation of mid-project review posters.

This file contains a series of posters by MPCA and U of M researchers (Gerard Blaha, Will DeRocher, Patricia Engelking, Nathan Johnson, Shannon Lotthammer, Phil Monson, Amy Myrbo, John Pastor, Joseph Sternberg, and Jennifer Holstad) compiled following the mid-project review of the Wild Rice study. In addition to an overview of the project including background and timeline, preliminary results are presented from ongoing field and laboratory studies.

MPCA (Minnesota Pollution Control Agency). 2013. Minnesota's sulfate standard to protect wild rice. Minnesota Pollution Control Agency. http://www.pca.state.mn.us/index.php/water/water-permits-and-rules/water-rulemaking/minnesotas-sulfate-standard-to-protect-wild-rice.html. Accessed June 14, 2013.

This website describes the MPCA project to review the Minnesota's sulfate standard with respect to wild rice. The website links to the above-referenced mid-project review file.

Meyer, M.W., P.W. Rasmussen, C.J. Watras, B.M. Fevold, and K. P. Kenow. 2011. Bi-phasic Trends in Mercury Concentrations in Blood of Wisconsin Common Loons during 1992-2010. Ecotoxicology 20(7):1659-1668.

Meyer, P. D., A. J. Valocchi, and W. Eheart. 1994. Monitoring network design to provide initial detection of groundwater contamination. Water Resources Research 30:2647-2659.

This paper proposes a method to design a groundwater monitoring network that minimizes the number of wells but provides adequate spatial coverage around a potentially contaminated site. Although the method is applied to initial detection of contamination at a landfill, it may have application to other types of sites. The method involves use of a simulation model to represent the target site and requires a good understanding of groundwater flow at the site.

MOE (Ministry of the Environment). 2012. Water and air baseline monitoring guidance document for mine proponents and operators (Interim Version). http://www.env.gov.bc.ca/epd/industrial/mining/pdf/water_air_baseline_monitoring.pdf

This publication from British Columbia describes methods for determining baseline conditions at a mine site. It gives advice on constituents to measure, sampling frequency, length of period to sample, and sampling locations.

Myette, C.F. 1991. Hydrology, water quality, and simulation of ground-water flow at a taconite-tailings basin near Keewatin, Minnesota U.S. Geological Survey, Water-Resources Investigations Report 88-4230, St. Paul, MN.

This report describes the hydrology of a large tailings basin. Surface- and ground-water quantity and quality are examined. Runoff from the basin was found to be small. The tailings basin contains a "mounded" water table, often less than 5 feet below the tailings surface. Water samples collected from wells and streams indicate that water leaving the basin area contains elevated levels of arsenic, fluoride, molybdenum, manganese, and nitrate+nitrite (fluoride, manganese, and nitrate+nitrite exceeded drinking water standards).

Ngatia, M, D. Gonzalez, S. San Julian, and A. Conner. 2010. Equivalence versus classical statistical tests in water quality assessments. Journal of Environmental Monitoring 12:172-177.

The paper by Ngatia et al. gives an example of equivalence testing in a water quality setting and points out advantages over standard null hypothesis significance tests.

Nater, E.A. and Grigal, D.F. 1992. Regional trends in mercury deposition across the Great Lakes states, north central USA. *Nature* 358: 139-141.

Nordstrom, K., 2012, Mine waters: acidic to circumneutral: Elements, v. 7, p. 393-398. http://www.researchgate.net/publication/236001211_Mine_waters_Acidic_to_circumneutral/file/504635176c3e4eb274.pdf.

This paper discusses the dissolution of pyrite and the common dissolved metal ions found in mine waters at a range of pH values. It concludes that although lower pH solutions contain more metals and higher concentrations of ions, that As, Sb, Mo, U, and F can be in high concentrations even in mine drainage that is near neutral pH.

NIOSH (National Institute for Occupational Safety and Health). 2005. Appendix C in Pocket Guide to Chemical Hazards (2005-149). NIOSH, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention.

This book describes occupational health and safety rules and guidelines for handling various industrial chemicals. Appendix C describes asbestos-specific guidelines, and was cited in material quoted from ATSDR 2008.

NorthStar Economics. 2011. The economic impact of the Gogebic taconite mine. Economic impact report, NorthStar Economics, Inc. for Gogebic Taconite, LLC. Available: http://www.wmc.org/cms/ wp-content/uploads/2012/02/GTAC_Impact_March_24.pdf, (Original report no longer available online. URL given links to the Wisconsin Manufacturers and Commerce archives.).

This report estimates the economic impact of a hypothetical iron mine in Northern Wisconsin. It is an advocacy report used by proponents of Northern Wisconsin mining in press materials. The report uses the IMPLAN input-output model (2008 year data) to derive direct, indirect, and induced effects from spending on mine operations (including tax impacts). The report assumes annual production of "8 million tons" (net or gross of waste not specified). The report does not specify other model assumptions such as mine revenue, linkage strengths, regional supply capacity, or timeline. It is impossible to validate the model results without these details. The report includes background information on economic impacts of mining in the U.S., Minnesota, and Michigan. (Note: These impact figures are based on national and regional input-output models, not on national income (GDP) figures. Use of I-O models in that way generally overstates impact and makes cross-sector and time series comparisons impossible.)

NTP (National Toxicology Program). 2011. Asbestos. Pages 53-55 *in* Report on carcinogens, twelfth edition. U.S. Department of Health and Human Services, National Toxicology Program, Research Triangle Park, North Carolina.

This is a brief by very informative summary of asbestos arcinogenity, geochemical properties, historical and modern uses and production figures, and exposure pathways. It also contains a summary of federal regulations relevant to asbestos.

Olivio, R. 2013. Iron mine could be ready for production within five years. Ashland Daily Press (May 9).

Palmer, M.A., E.S. Bernhardt, W.H. Schlesinger, K.N. Eshleman, E. Foufoula-Georgiou, M.S. Hendryx, A.D. Lemly, G.E. Likens, O.L Loucks, M.E. Power, P.S. White, and P.R. Wilcock. 2010. Mountaintop mining consequences. Science 327:148-149.

This Science Policy Forum article gives a broad overview of the ecological consequences of mountaintop mining with valley fills, which is the predominant mining activity in the central Appalachian region. Some of the issues outlined, however, are potentially relevant to open-pit taconite mining, such as the consequences of large-scale watershed disturbances and selenium contamination.

Parkhurst, D. F. 2001. Statistical significance tests: Equivalence and reverse tests should reduce mininterpretation. BioScience 51:1051-1057.

This paper describes equivalence tests for a general audience and gives interesting biological applications. These examples highlight the difference in interpretation between equivalence tests and standard null hypothesis significance tests.

Pedersen, E. and M. Johansson. 2012. Wind power or uranium mine: appraisal of two energy-related environmental changes in a local context. *Energy Policy* 44:312-319.

This paper presents an applicable understanding of the fragile issue of introducing major environmental changes into a rural residential area. Pedersen and Johansson (2012) explored community response to anticipated changes in the local environment resulting from a wind farm and exploratory uranium drilling as they relate to factors predicting beneficial or adverse appraisals of environmental changes. The study took place in a setting analogous to northern Wisconsin; an inland rural setting with low population density that included scenic qualities and recreation opportunities. Residents lived in dwellings on or very near lakes or forests which provided opportunities for hunting and fishing. The authors note that an individual's appraisal of environmental change is influenced by his or her previous experiences and attitudes towards the sources of stress. Consequently, introducing technical or industrial activities (e.g., wind farms or uranium drilling in Sweden or a taconite mine in Wisconsin) to such an environment could be appraised as threatening. A succinct summary of their findings is that psychological factors such as concerns for the environment (exhibited as pro-environmental behavior), valuing closeness to nature and involvement in town meetings (intended to assist with appraisal) can actually hinder the appraisal process and should be considered when new developments affecting the environment are presented.

Pfeil, J. 2005. Economic impact of mining on New Mexico. In [15], chapter 3, pages 90–95. Available: http://geoinfo.nmt.edu/publications/decisionmakers/2005/.

Plumlee, G.S. and S.A. Morman. 2011. Mine wastes and human health. Elements, 7: 399-404.

This is a short review of chemical and hazardous conditions encountered around mine sites. It is written concisely, and is a good general introduction to the topic.

Pond, G.J., M.E. Passmore, F.A. Borsuk, L. Reynolds, and C. J. Rose. 2008. Downstream effects of mountaintop coal mining: comparing biological conditions using family- and genus-level macroinvertebrate bioassessment tools. Journal of the North American Benthological Society. 27: 717-737.

Benthic macroinvertebrates communities were adversely affected by metals from mining activities in central Appalachian Mountains. Ephemeroptera were especially adversely affected.

Poulton, B.C., A.L. Albert, J.M. Besser, C.J. Schmitt, W.G. Brumbaugh, and J.F. Fairchild. 2010. A macroinvertebrate assessment of Ozark streams located in lead-zinc mining areas of the Viburnum Trend in southeastern Missouri, USA. Environmental Monitoring and Assessment. 163:619-641.

This study compared macroinvertebrate communities below mine sites and compared them with reference sites. Reference sites were fully supporting of aquatic life while sites downstream of mining and related activities were partially supporting, with biotic condition scores 10% to 58% lower than reference sites.

Power, T. M. 1996. Lost Landscapes and Failed Economies: The Search For A Value Of Place. Island Press, Washington, DC.

This book argues that "the quality of the natural landscape is an essential part of a community's permanent economic base and should not be sacrificed in short-term efforts to maintain employment levels in industries that are ultimately not sustainable." The book is both a scholarly work and an advocacy piece. The author evaluates the long-term economic development aspects of "extractive industries" around the world, including ranching, mining, and timber industries. He contrasts the extractive model against a place-based model of development, which emphasizes the roles of individual location decisions; labor supply; and environmental and community quality.

Power, T. M. 2005. The economic anomaly of mining—great wealth, high wages, declining communities. In [15], chapter 3, pages 96–99. Available: http://geoinfo.nmt.edu/publications/decisionmakers/ 2005/.

This paper explores the "contrast between the wealth created and the high wages paid in mining and the poor economic performance of mining communities". Relying on public data from the U.S. Department of Agriculture and U.S. Census Bureau, the paper documents the poor economic performance of mining-dependent counties compared to other counties. That poor performance is in contrast with relatively high wages paid to mine employees and relatively high per-firm revenue in mining. The paper argues that the inconsistency is explained by the instability of mining employment and income. The paper argues that labor income from mining has a boom-and-bust quality that hinders broader economic development. Furthermore, mining has become significantly less labor-intensive in the last few decades, futher reducing the relevance of mining income to economic development.

Power, T. M. 2007. The economic role of metal mining in Minnesota: Past, present, and future. Report prepared for Minnesota Center for Environmental Advocacy and the Sierra Club, Economics Department, University of Montana, Missoula, Montana. Available: http://bit.ly/14Mf5b4.

This report provides a general overview of the role of metallic mining in the state and local economies of Minnesota. It combines a scholarly review of public data on mining economics with an advocacy position about the role of mining in economic development. The report summarizes long-term trends in mining income and employment; mining labor volatility; and the use of input-output models to assess economic impacts of mining projects. The report closes with an argument in favor of "amenity supported" economic development over the "basic industry" (or "extractive") model of development.

Power, T. M. 2011. A more holistic economic evaluation of mining: Considering benefits and costs (understanding the impacts of mining in the western Lake Superior region). Presentation given to the USGS workshop, Bad River Reservation, Wisconsin, September 12-14.

Price, L. G., D. Bland., V. T. McLemore., and J. M. Barker., editors 2005. Mining in New Mexico: The Environment, Water, Economics, and Sustainable Development. Decision Makers Field Guide Series. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. Available: http://geoinfo. nmt.edu/publications/decisionmakers/2005/.

This field guide is an anthology of 30 articles addressing science and policy issues related to mining in New Mexico. The guide addresses the physical and historical framework for New Mexico mining; environmental and water quality issues; economic impacts; policy and regulatory issues; and sustainability and future development.

Renner, R. 2005. Proposed selenium standard under attack. Environmental Science and Technology 39(6):125A-126A.

This news article reports on the controversy surrounding U.S.EPA's selenium guidelines for fish tissue. Because of the bioaccumulative nature of selenium, a chronic criterion based on fish tissue concentrations was adopted, of 7.9 ppm dry weight. Five scientists (including Dennis Lemly, on whose study the criterion was based) submitted a critique of this regulation, suggesting that 5.85 ppm dry weight should be chosen instead, and that the 7.9 ppm value is not adequately protective of wildlife.

Richards, R.T. and R.L. Brod. 2004. Community support for a gold cyanide process mine: resident and leader differences in rural Montana. *Rural Sociology* 69:552-575.

This paper investigated how rural communities confront development proposals that involve uncertain risks. Specifically, they investigated community support (differentiating community leaders from residents) for a gold cyanide process (GCP) mine in Montana. They conclude with a recommendation that rural communities facing projects characterized by new and unfamiliar technology should approach these developments as "*new species of trouble* (Erickson, 1994) that can be more fully understood through case comparisons."

Robertson, D. M. and E. D. Roerish. 1999. Influence of various water quality sampling strategies on load estimates for small streams Water Resources Research 35:3747-3759.

The Robertson and Roerish paper examines the effect of sampling frequency on estimates of load for small streams. It specifically considers aspects of sampling that are related to stream flow.

Ross, M., R.P. Nolan, and G.L. Nord. 2008. The search for asbestos within the Peter Mitchell Taconite iron ore mine, near Babbitt, Minnesota. Regulatory Toxicology and Pharmacology 52:S43-S50.

This paper examines samples from 30 sites in this mine pit, which has previously been the subject of an asbestos-related controversy (see Berndt and Brice 2008). Significant amounts of fibrous materials were found in many samples. These materials were determined not to be asbestos, however, and the authors suggest that that do not present a significant health hazard.

Schlager, R., J. Amrhein, and K. Bowell. (2012). Developing Cost Effective Solutions to Reduce Mercury from Minnesota Taconite Plants - Hibbing Taconite Plant. Minnesota Department of Natural Resources. St. Paul, MN: 151 p.

This report is from a private consultant commissioned by the Minn. Dept. of Natural Resources to test activated carbon as a mercury sorbent in process gas during curing of taconite pellets. Field tests were conducted at the ArcelorMittal site in Virginia MN. The report concludes that activated carbon (AC) in process gas lowers mercury emissions, but that techniques employing AC vary in their cost-effectiveness.

Schmidt, R.G., 1951, The subsurface geology of Freedom township in the Baraboo iron-bearing district of Wisconsin: University of Wisconsin, Madison, Master's thesis, 40 p.

Schmidt described the geology of the iron ore in the Freedom Formation in the Baraboo Syncline based on drill cores and mine workings.

Schmidt, R.G., 1980, The Marquette Range Supergroup in the Gogebic iron district, Michigan and Wisconsin: U.S. Geological Survey Bulletin 1460, 32 p. pdfhttp://pubs.usgs.gov/bul/1460/report.pdf

This paper is the most detailed description of the rocks in the Gogebic-Penokee Range including the Ironwood Formation and adjacent units. The members of the Ironwood are described in detail. The mineralogy of each member is mentioned although little attention is given to pyrite or amphibole.

Schot, P. P. and S. M. Peiber. 2012. Spatial and temporal variations in shallow wetland groundwater quality. Journal of Hydrology 422-423: 43-52.

This paper estimates spatial and temporal variability in several constituents from a network of groundwater wells near a wetland in the Netherlands. The investigators found that spatial variability was generally three times as large as temporal variability in the constituents they measured.

Schuirmann, D. J. 1987. A comparison of two one-sided tests procedure and the power approach for assessing the equivalence of average bioavailability. Journal of Pharmacokinetics and Biopharmaceutics 15:657-680.

Schuirmann's paper is the first description of the two one-sided tests (TOST) procedure for equivalence testing. This procedure has since become one of the most frequently used equivalence tests. Although he applied the test in studies of drug equivalency, it has applications in many other fields.

Simmons, B.D. and D. Wallschlager, 2005. A critical review of the biogeochemistry and ecotoxicology of selenium in lotic and lentic environments. Environmental Toxicology and Chemistry 24(6):1331-1343.

This is a thorough review of studies of selenium in the environment, with an emphasis on describing potential differences between lakes/reservoirs and rivers/streams. Taken as a whole, the literature and fundamental considerations suggest that biomagnification of selenium is less severe in flowing waters, though this has not been directly tested.

Skalski, J. R. and D. H. McKenzie. 1982. A design for aquatic monitoring programs. Journal of Environmental Management 14:237-251.

This paper describes a method for environmental impact assessment. Although the paper describes impact assessment at a nuclear power plant, the method can be applied at any site where a change, usually due to human activities, can be anticipated so that monitoring begins before the change occurs. The procedure involves pairing an impacted site with a control site that has similar characteristics.

Skorupa, J.P., T.S. Presser, S.J. Hamilton, A.D. Lemly, and B.E. Sample. 2004. EPA's draft tissue-based selenium criterion: A technical review.

This is the report referred to in the Renner (2005) news article. It was delivered to EPA in June, 2004. It provides a detailed explanation of why 7.9 ppm dry weight in fish tissue is not an adequately protective chronic criterion. The methodology of the A.D. Lemly study, on which the value was based, was not appropriately taken into account. Information on selenium exposure risk and effects for various species is provided.

Skousen, J., Renton, J., Brown, H., Evans, P., Leavitt, B., Brady, K.B.C, Cohen, L., Ziemkiewicz, P., Neutralization potential of overburden samples containing siderite: Journal of Environmental Quality, v. 26, p. 673-681.

This paper details the neutralization potential of mine waste rock and concludes that calcite has significant neutralizing capabilities whereas siderite does not because it is less soluble and upon dissolution releases iron ions that participate in dissolution of pyrite.

Smith, E. P. 2002. BACI design. Pages 141-148 *in* A. H. El-Shaarawi and W. W. Piegorsch, editors. Encyclopedia of Environmetrics, Volume 1. Wiley. New York.

Smith's article describes the Before-After-Control-Impact (BACI) design that has become standard in evaluating environmental impacts and management changes. He describes the characteristics of the design and available methods of analysis.

Steenland, K. and Brown, D. (1995). Mortality study of gold miners exposed to silica and nonasbestiform amphibole minerals: An update with 14 more years of follow-up. *American Journal of Industrial Medicine,* 27:217-229.

This is a long-term study of over 3,000 gold miners who were exposed to (non-asbestos) amphibole minerals and silica dust. There was not evidence of an increased lung cancer risk among this group. However, there was an elevated risk of other diseases known to be associated with silica exposure (e.g., tuberculosis, silicosis, etc.).

Stewart-Oaten, A., W. W. Murdoch, and K. R. Parker. 1986. Environmental impact assessment: "Pseudoreplication" in time? Ecology 67:929-940.

This paper is one of the early discussions of designs and analyses for evaluating environmental impact. In it, the authors describe the Before-After-Control-Impact (BACI) design and present a method for data analysis.

Stuart, W.T., E.A. Brown, and E.C. Rhodehamel. 1954. Ground water investigations of the Marquette iron-mining district. Michigan Department of Conservation, Geological Survey Division, Lansing, Michigan.

This is a detailed study on the groundwater hydrology in the Marquette iron mining district in northern Michigan. The purpose of this research was to better characterize flowpaths in order to optimize dewatering activities. Groundwater moves through the bedrock via fractures in this regions. Abandoned mine workings and dewatering pumping have altered flow patterns.

Sunstein, C. R. 2013. The real world of cost-benefit analysis: Thirty-six questions (and almost as many answers). Working paper, Harvard Law School.

Swenson, D. 2006. Input-outrageous: The economic impacts of modern biofuels production. Technical report, Department of Economics, Iowa State University. Available: http://www.econ.iastate.edu/ research/webpapers/paper_12644.pdf.

This paper describes the errors and misrepresentations that are common in input-output modeling of the local economic impacts of bioenergy facilities. The lessons are generally applicable to such models. Cautions include failure to distinguish cause from effect; failure to understand the static nature of input-output models; failure to account for slack and leakages in the local economy; failure to consider scale economies; omission of regional offsets; omission of unpriced externalities; and failure to specify time scale and duration. The paper concludes with a revised estimate of Iowa biofuel impacts, correcting for the cautions listed.

Tuck, C.A. and R.L. Virta. 2013. Iron Ore. Pages 39.1-39.17 *in* 2011 Minerals Yearbook. U.S. Geological Survey, Reston, Virginia.

USBOM (U.S. Bureau of Mines). 1987. Surface Mine Blasting, Proceedings of the Bureau of Mines Technology Transfer. U.S. Bureau of Mines, Information Circular 9135, Chicago, Illinois.

This document summarized Bureau of Mines research on blasting technology that were presented at a seminar on April 15, 1987. It includes studies on a number of topics, including safety, timing issues, and vibration and airblast.

US EPA (1993) Method 300.0 Revision 2.1. Determination of Inorganic Anions by Ion Chromatography. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

USEPA (U.S. Environmental Protection Agency). 1994a. Technical Resource Document, Extraction and Beneficiation of Ores and Minerals, Volume 3: Iron. U.S. Environmental Protection Agency, Office of Solid Waste, EPA 530-R-94-030, Washington, D.C.

Excellent overview of iron mining practices in the U.S. in 1994 (taconite ores), with an emphasis on waste production in the context of the Resource Conservation and Recovery Act (RCRA) and associated environmental effects. Also includes an overview of the federal and state (Minnesota and Michigan) regulatory frameworks, and documents an EPA site visit for the LTV (now Cliffs Erie) mine (Dunka Pit), which now in closure. Because the taconite ore here is adjacent to copper-nickel sulfide deposits, this site has a history of acid mine drainage and release of copper and nickel to surface water.

USEPA (U.S. Environmental Protection Agency). 1994b. Acid mine drainage prediction, Technical Report http://water.epa.gov/polwaste/nps/upload/amd.pdf

This detailed report describes the static and kinetic tests conducted on rocks as well as mathematical modeling to predict the acid-generating potential of waste-rock piles. Case studies include the waste rock associated with the Dunka Pit iron mine in Minnesota that removed copper and nickel-bearing gabbro as waste rock.

US EPA (1994c) METHOD 200.7 Revision 4.4. Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma-Atomic Emission Spectrometry. Environmental Monitoring Systems Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

US EPA (1996) Method 1669, Sampling Ambient Water for Determination of Trace Metals at EPA Water Quality Criteria Levels. U.S. Environmental Protection Agency, Office of Water Engineering and Analysis Division, Washington, D.C. This sampling method was designed to support water quality monitoring programs authorized under the Clean Water Act.

USEPA (U.S. Environmental Protection Agency). 1997a. Taconite Ore Processing. Pages 11.23-1 to 11.23-19 *in* AP-42, Compilation of Air Pollutant Emission Factors. USEPA, Air Quality Planning and Standards/Office of Air and Radiation. Research Triangle Park, North Carolina.

This document provides technical information related to air pollutant emissions from taconite processing. Emission factors are provided for major and minor pollutants, tabulated by the different types of processes/equipment used in the industry. It also provides a good overview of taconite beneficiation processes, with an emphasis on points of air emissions.

USEPA (U.S. Environmental Protection Agency). 1997b. Mercury study report to Congress. Vol VI: An ecological assessment for anthropogenic mercury emissions in the United States (EPA-452/R-97-008). USEPA, Washington, D.C.

This report broadly considers ecological problems associated with mercury in the environment, and reviews mercury cycling in air, water and soil, exposure pathways, ecological effects, systems at risk, bioaccumulation, fate, and effects to various categories of wildlife.

US EPA (2001) Method 1630 Draft, Methyl Mercury in Water by Distillation, Aqueous Ethylation, Purge and Trap, and CVAFS. U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Engineering and Analysis Division, Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2002a. Economic Impact Analysis of the Proposed Taconite Iron Ore NESHAP, Final Report. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, EPA-452/R-02-013, Research Triangle Park, NC.

This report examines the economic impacts of compliance with national emission standards for hazardous air pollutants (NESHAP) on the taconite processing industry. Section 2 is a taconite mining and processing industry profile prepared by the Research Triangle Institute Center for Regulatory Economics and Policy Research. The taconite pellet production process is described, and data on the mines in Minnesota and Michigan in operation in 2000 is summarized.

US EPA (2002b) Method 1631 Revision E, Mercury in Water by Oxidation, Purge and Trap, and Cold Vapor Atomic Fluorescence Spectrometry. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2003a. EPA and hardrock mining: A source book for industry in the Northwest and Alaska. USEPA Region 10, Seattle, WA.

The primary purpose of this document is to describe the requirements of the Clean Water Act and the National Environmental Policy Act as they pertain to the permitting and monitoring of new mines. Although written specifically for mines in the Northwestern US and Alaska, most of these requirements apply to the entire US. Appendix A explains the methods used to characterize the surface water hydrology, groundwater hydrogeology, and the surface water-groundwater interactions at a mine site. This information is required for development of an Environmental Impact Statement and for evaluating baseline conditions used in comparisons with monitoring data acquired after the mine is in operation. Appendix B describes methods to characterize water quality at a mine site. It also describes procedures for designing a program to monitor water quality to evaluate mining impacts.

USEPA (U.S. Environmental Protection Agency). 2003b. Libby asbestos site, residential/commercial cleanup, action level and clearance criteria: Technical memorandum (Draft Final- Dec. 15, 2003). U.S. Environmental Protection Agency, Region 8.

US EPA (2003c) Method 8000C Revision 3. Determinative Chromatographic Separations. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846 On-Line, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, D.C.

US EPA (2007a) Method 6020A Revision 1. Inductively Coupled Plasma-Mass Spectrometry. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846 On-Line, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, D.C.

US EPA (2007b) Method 3500C Revision 3. Organic Extraction and Sample Preparation. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846 On-Line, U.S. Environmental Protection Agency, Office of Solid Waste, Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2009. Statistical analysis of groundwater monitoring data at RCRA facilities – Unified Guidance. USEPA Report 530/R-09-07, Washington, D. C.

This document provides a long and comprehensive review of statistical methods used for analyzing data from groundwater monitoring wells at facilities that treat, store, or dispose of hazardous waste. Some of these methods could be used for analysis of data from groundwater monitoring at mines.

USEPA (U.S. Environmental Protection Agency). 2010. Guidelines for preparing economic analyses. Report EPA 240-R-10-001, National Center for Environmental Economics, Office of Policy, USEPA, Washington, DC. Available: http://yosemite.epa.gov/ee/epa/eed.nsf/pages/ Guidelines.html.

This report provides lengthy (272 pages) and detailed guidance on the use of economic analyses in rule-making by the U.S. Environmental Protection Agency. It includes a glossary; summary of statutory and administrative requirements for regulatory economic analysis; general concepts in environmental policy design; establishment of a baseline; discounting methods; benefits analysis; costs analysis; and guidance on presentation. Appendices address economic theory, mortality risk, and accounting for unemployment.

USEPA (U.S. Environmental Protection Agency). 2012a. Basic Information about Asbestos in Drinking Water. USEPA, Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2012b. 40 CFR 1502 — environmental impact statement. Code of Federal Regulations. Available: http://www.gpo.gov/fdsys/granule/CFR-2012-title40-vol34/ CFR-2012-title40-vol34-part1502/content-detail.html.

US EPA (2012c) 29758 Federal Register / Vol. 77, No. 97 / Friday, May 18, 2012 / Rules and Regulations, Environmental Protection Agency 40 CFR Parts 136, 260, 423, 430 and 435, Guidelines Establishing Test Procedures for the Analysis of Pollutants under the Clean Water Act; Analysis and Sampling Procedures. Final Rule.

USGS (U.S Geological Survey). 2005. Mineral Resources Data System. U.S. Geological Survey, Reston, Virginia. Accessed online at http://mrdata.usgs.gov/mrds.

The Mineral Resources Data System (MRDS) is a geospatial data set describing mineral resource occurrence throughout the world. It subsumes the Mineral Availability System/Mineral Industry Locator System (MAS/MILS) of the former U.S. Bureau of Mines. These data describe current and historical prospects, mines, and processing facilities.

WAC (Wisconsin Administrative Code). 2004. Control of Asbestos Emissions. WAC, Ch. 447.

Walton, 1982, The nature, hazards, and assessment of occupational exposure to airborne asbestos dust: a review: The Annals of Occupational Hygiene, v. 25, no. 2, p. 117-119. http://annhyg.oxfordjournals.org/content/25/2/117.short

This paper discusses asbestos counting methods and the length and aspect ratio of fibers that are human health hazards. The paper suggests that fibers 5 – 100 μm long and < 1.5μm wide with an aspect ratio of 5:1 are hazardous, which are different ranges than the previously established standards. The smallest fibers are difficult to detect but can be a significant portion of total mass of airborne asbestos. The potential health hazard is dependent on the mineralogy as well as the size of the fibers.

Ward, R. C. and J. C. Loftis. 1986. Establishing statistical design criteria for water quality monitoring systems: Review and synthesis. Water Resources Bulletin. 22: 759-767.

Ward and Loftis review statistical methods used in the analysis of water quality monitoring data. They use information from this review to examine principles of design for monitoring programs. This is one of the early papers incorporating statistical principles in monitoring design.

Ward, R. C., J. C. Loftis, K. S. Nielsen, and R. D. Anderson. 1979. Statistical evaluation of sampling frequencies in monitoring networks. Journal (Water Pollution Control Federation) 51:2292-2300.

This is one of the first papers to use statistical sample size calculations to determine optimal sampling frequencies for monitoring water quality.

Watras, C.J. 2009. Mercury pollution in remote freshwaters. In Gene. E. Likens (ed). Encyclopedia of Inland Waters, Oxford, Elsevier, vol. 3, pp 100-109.

Watras, C.J., K.A. Morrison, and R.C. Back. 1996. Mass balance studies of mercury and methylmercury in small, temperate/boreal lakes of the northern hemisphere. in W. Baeyens, R. Ebinghaus, and O. Vasiliev [eds]. Regional and Global Mercury Cycles: Sources, Fluxes and Mass Balances. NATO Advanced Science Institute Series 2: Environment - Vol. 21, pp 329-358. Kluwer.

Watras, C.J., K.A. Morrison, O. Regnell, T.K. Kratz. 2006. The methylmercury cycle in Little Rock Lake during acidification and recovery. Limnol. Oceanogr. 51(1):257-270.

Watras, C. J., K. A. Morrison, J.L. Rubsam, and B. Rodger. 2009. Atmospheric mercury cycles in northern Wisconsin. *Atmospheric Environment* 43(26): 4070-4077.

WDNR (Wisconsin Department of Natural Resources). 1990. The Kennecott Flambeau mine process documents: Final environmental impact statement. Bureau of Environmental Analysis and Review. Available: http: //digital.library.wisc.edu/1711.dl/EcoNatRes.FinEnvImpMar90.

his report is the final economic impact statement for the Flambeau mine. It describes the project as it was then proposed, describes the affected environment, evaluates impacts, lists and evaluates alternatives, and reproduces public comments received. Backmatter lists contributors, information sources, and gives technical details on species and water quality.

WDNR (Wisconsin Department of Natural Resources). 1994. Internal notes on findings from the Department's Northern Initiative.

In 1994 the Department of Natural Resources undertook a Northern Initiatives project with a goal to garner as much public input as possible, inviting citizens to diagnose present problems and future goals in the management of northern Wisconsin's natural resources. Public input was solicited by means of a questionnaire (referred to as an opinionnaire to reflect its non-scientific distribution) that was distributed across northern Wisconsin at 28 Northern Initiatives open houses and other private and public functions. It was available at DNR field stations across the North and published in various newspapers in the North Central District. All in all the DNR received 2,347 opinionnaires. Additional comments were noted and consolidated by DNR personnel who staffed the open houses.

WDNR (Wisconsin Department of Natural Resources).1997a. Local decisions in metallic mining projects. Mining information sheet, WDNR. Available: http://dnr.wi.gov/topic/Mines/documents/loc-dec.pdf.

This Mining Information Sheet explains the zoning and local agreement powers available to local governments related to mining projects. (Note that the sheet has not been updated since 1997.)

WDNR (Wisconsin Department of Natural Resources). 1997b. Cumulative impacts of metallic mining development in Northern Wisconsin. Mining information sheet, WDNR. Available: http://dnr.wi.gov/topic/ Mines/documents/cml-imp.pdf.

This Mining Information Sheet explains the concept of cumulative impacts of mining and discusses relevant factors like resource impacts, socioeconomic impacts, and arguments for and against the use of cumulative impacts analysis. (Note that the sheet has not been updated since 1997.)

WDNR (Wisconsin Department of Natural Resources). 1997c. Wisconsin's Net Proceeds Tax on Metallic Mining and Distribution of Funds to Municipalities. Mining information sheet, WDNR. Available: http: //dnr.wi.gov/topic/Mines/documents/net-tax.pdf.

This Mining Information Sheet explains the Net Proceeds Tax, established in 1977, including legislative intent, timing of the tax, deposit of the tax into the Mining Impact Fund, and various payments to local governments from the fund. (Note that the sheet has not been updated since 1997.)

WDNR (Wisconsin Department of Natural Resources). 2012. Choose wisely – 2012: A health guide for eating fish in Wisconsin (PUB-FH-824 2012). WDNR Bureau of Fisheries Management.

This is a booklet published by the Wisconsin Department of Natural Resources. It is a list of Wisconsin waters impaired with the presence of fish containing unhealthy concentrations of mercury or PCBS, and contains specific advice on fish consumption to minimize exposure.

WDNR (Wisconsin Department of Natural Resources). 2013. Chapter NR 150: Environmental analysis and review procedures for department actions. Wisconsin Administrative Code. Available: http://docs.legis. wisconsin.gov/code/admin_code/nr/100/150.pdf.

WDOR (Wisconsin Department of Revenue). 2003. Mining Investment and Local Impact Fund Board: 2001–2003 Biennial Report. WDOR Website. Available: http://www.revenue.wi.gov/report/m.html.

This report briefly describes the board and its membership, and summarizes fund income and disbursements for the 2001–2003 biennium. The report notes that no metallic mining occurred in the state during the biennium nor was any anticipated in the near future. (As of this writing, no subsequent biennial reports are available from the Department of Revenue, which administers the fund.)

Weidman, S., 1904, The Baraboo iron-bearing district of Wisconsin: Wisconsin Geological and Natural History Survey, Bulletin 13, 190 p.

This is a detailed description of the iron ore and related geology of the Baraboo district.

WGNHS (Wisconsin Geological and Natural History Survey). 2011. Iron mining in Wisconsin. WGNHS, Factsheet 3, Madison, Wisconsin.

Zanko, L.M. 2011. Cost comparison of underground and surface mining options for potential western Mesabi range iron ore resources. Natural Resources Research Institute, University of Minnesota, Duluth, NRRI/TSR-2011/01, Duluth, Minnesota.

This modeling analysis examines the hypothetical extent of underground and surface taconite mining operations along the Western Mesabi iron range in Minnesota, utilizing an economic modeling approach. Surface mining is determined to be more cost effective when the stripping ratio (ratio of overburden to ore) is less than 6:1. It appears unlikely that underground mining of less-accessible taconite deposits will be economically feasible in the foreseeable future.

Zheng Z., H. Niu, H.H. Gerke, R.F. Hüttl. 1998. Pyrite oxidation related to pyritic mine site spoils and its controls: A review. Chinese Journal of Geochemistry 17:2, 159-169.

Zhou, Y. 1996. Sampling frequency for monitoring the actual state of groundwater systems. Journal of Hydrology 180:301-318.

Zhou's paper presents methods for determining groundwater sampling frequency for three objectives: 1) detection of trend; 2) determination of periodic fluctuations; and 3) estimation of mean. An initial time series analysis of available data is necessary to obtain parameter estimates on which sampling frequency decisions can be based.

APPENDIX A: RESOURCES FOR METHODS OF SOCIAL INQUIRY

Surveys

Converse, J.M. and S. Presser. 1986. Survey questions: handcrafting the standardized questionnaire. Sage Publications. Newbury Park, CA.

Based on the classic work of Stanley Payne, this volume explains the guiding principles for writing survey questions.

Dillman, D.A., J.D. Smyth and L.M. Christian. 2008. Internet, mailed, and mixed-mode surveys: the Tailored Design Method. John-Wiley & Sons. Hoboken, NJ.

The Tailored Design method is considered the standard for survey research by which most researchers follow. The text provides a complete guide to the conduct of Internet, mail and telephone surveys.

Frey, J.H. 1989. Survey research by telephone. Sage Publications. Newbury Park, CA.

An informative text intended for the researcher with some familiarity with surveys but is looking for detailed guidance on the conduct of telephone surveys in particular.

NOAA Coastal Services Center. 2007. Introduction to survey design and delivery. Charleston, SC.

This is an easy-to-read practical guide designed for the novice survey researcher. The document provides insight into the various types and methods of survey research along with helpful guides to sampling and analysis terms and survey types.

Payne, S.L. 1951. The art of asking questions. Princeton University Press. Princeton, NJ.

The classic text on how to write effective questions.

Focus Groups

Krueger, R.A. and M.A. Casey. 2009. Focus groups: a practical guide for applied research. Sage Publications. Thousand Oaks, CA.

Another must-have reference that offers an easy-to-read overview of sound focus group practices. Absent of theory, it provides hands-on advice to researchers needing to conduct focus group interviews.

NOAA Coastal Services Center. 2009. Introduction to conducting focus groups. Charleston, SC.

An easy-to-read practical guide designed for the novice focus group researcher.

Interviews

Fowler, F.J. and T. Mangione. 1990. Standardized survey interviewing: minimizing interviewer-related error. Sage Publications. Newbury Park, CA.

This is a practical guide describing how to conduct interviews which minimize the error than can be attributed to interviewers.

McCracken, G. 1988. The long interview. Sage Publications. Newbury Park, CA.

A provision of theory and methods of the long qualitative interview. The author outlines a simple four-step model of inquiry, from the design of an open-ended questionnaire to reporting the results.

Social and Stakeholder Assessments

Bright, A.D., H.K. Cordell, A.P. Hoover and M.A. Tarrant. 2003. A human dimensions framework: guidelines for conducting social assessments. U.S. Department of Agriculture Forest Service. Asheville, NC. Gen. Tech. Rep. SRS-65. 83 p.

Although focusing on forest planning, this report provides a framework and guidelines for the conduct of human dimensions research which would be applicable to most resource management situations.

Jolley, G.J. 2007. Public involvement tools in environmental decision-making: a primer for practitioners. *Journal of Extension* 45(2).

An easy-to-read paper which provides an overview of appropriate public involvement tools when resource and time constraints do not allow for a prolonged public deliberation process. The strengths and weaknesses of three public involvement tools are discussed: citizen surveys, public hearings/meetings and stakeholder interviews.

Risk Communication

Morrow, B.H. 2009. Risk behavior and risk communication: synthesis and expert interviews. NOAA Coastal Services Center. Charleston, SC.

This report synthesizes the existing social science research findings on risk behavior and risk communication with a goal of assisting risk communicators. The report also provides real-world examples, based on interviews with people active in risk communication, of effective ways to facilitate behavior that reduces the risk to people and property.

NOAA Coastal Services Center. 2009. Understanding risk behavior: the fundamental challenges. Charleston, SC.

An easy-to-read summary of suggestions and best practices for communicating risks and changing public behavior.

APPENDIX B: EQUIVALENCE TESTS

Standard statistical significance tests involve two types of error: the error (denoted α) of rejecting the null hypothesis when it is actually true, and the error (denoted β) of not rejecting the null hypothesis when it is false. The tests are formulated so that the probability of making the first type of error (α) is minimized, typically held to less than 0.05. The second type of error (β) is not specifically addressed by the test, except through the design of the study, by ensuring that the sample size is large enough to keep this error small. In practice, the second type of error is often ignored, so that the probability of making that type of error may be quite large when the sample size is small. This can be an important issue in compliance situations, because the traditional formulation of the null hypothesis may result in a site appearing compliant when the sample size is small, but appearing to be in violation when the sample size becomes large, even though the mean difference from reference conditions has not changed. It may help to consider an example that illustrates this issue.

Consider a situation in which an unimpacted stream and a stream running through a mine site are both sampled quarterly, starting 2 years before the mine begins operation and continuing thereafter. A standard approach to analyzing such data might be to compute the difference in concentrations between the two streams at each time of sampling, and to use the differences from the early period as a sample of reference conditions. Then similar differences from the period after the mine is operating could be compared to the pre-operation differences using a simple test such as a two sample t-test (Stewart-Oaten et al. 1986). In this case, the standard null hypothesis is that there is no difference between the two time periods. Thus, we are minimizing the error of concluding that the mine has changed conditions (rejecting the null hypothesis) when it hasn't, but the probability of detecting a statistically significant change in conditions when such a change has actually occurred may be very low. This is sometimes referred to as minimizing the producer's risk, while not explicitly controlling the consumer's risk (see, e.g., Cade 2011). In this situation, as the post-operation sample size gets large, even very small and biologically unimportant differences between the two time periods may be statistically significant. Such a test does not seem appropriate for environmental regulation.

An equivalence test in this situation would specify a null hypothesis that is in some sense the opposite of the standard null hypothesis. For instance, if any change of less than 20% from the baseline conditions would be considered equivalent to those conditions, the null hypothesis for the equivalence test would then be that the two time periods differ by more than 20%. Standard tests for this null hypothesis are available (Schuirmann 1987, Berger and Hsu 1996) and can be carried out with many statistical software packages. In this case, we are minimizing the error of concluding that the mine has not changed conditions when it has. If there is a large difference between the time periods it should be detected with a moderate sample size. If there is only a small difference between the two time periods, this will never result in a significant difference, even when the sample size becomes very large. This behavior is consistent with the intuition of most analysts about how a test should perform in this situation.

APPENDIX C: OVERVIEW OF RELEVANT ANALYTICAL METHODS

C.1. GENERAL CHEMISTRY

Some general parameters to measure include Alkalinity (Total, Bicarbonate, Carbonate), Specific Conductance, pH, TDS (Total Dissolved Solids), TSS (Total Suspended Solids), BOD (Biochemical Oxygen Demand), TOC (Total Organic Carbon), Ammonia-Nitrogen, Nitrate-Nitrogen, TKN (Total Kjeldahl Nitrogen), Total Phosphorus, Chloride and Sulfate. Some methods for general chemistry parameters include gravimetric assays, electrometric / titration assays, colorimetric, oxidation-combustion and ion chromatography technologies. Depending on the matrix, parameter, method and other regulations, additional sample preparation techniques are required, some of which include water leaching, distillation, and acid digestion.

The ion chromatography analytical technique is commonly used to measure anions. Common anions include fluoride, chloride, nitrate, nitrite, *ortho*-phosphate and sulfate. Anions in the samples are separated using columns and measured with a conductivity detector. The chromatograms of the anions are evaluated to ensure there is complete resolution between the peaks and that retention window criterion is met. As with other analysis, there are specific calibration and quality control requirements. Solid samples can be analyzed after an extraction procedure is completed. (US EPA 300.0).

C.2. METALS

Metals in natural freshwaters can be divided into two general classes: 1) minor metals, such as Al and Fe; and 2) trace metals, such as Cd, Pb and Hg. Numerous studies have shown that extreme care must be taken during sample collection, handling, storage and analysis to avoid contamination artifacts that can inadvertently elevate estimated metal concentrations in natural waters. This is particularly true for trace metals like Hg and Pb where inadvertent contamination can yield errors approaching 3 orders of magnitude; but it also applies to many minor metals in relatively pristine waters.

Care must be taken to use the approved methods/technologies for the relevant regulatory program since there are differences in applicability depending on the parameter and matrix. Also, consideration for the sensitivity of the technique chosen must meet the specified data quality objectives wherever possible. There are a variety of approved sample preparation methods. Some of the analytical techniques are briefly described below for the analysis of Al, Sb, As, B, Ba, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Ni, K, Se, Ag, Sr, Na, Tl, V, Zn and Hg. These are not all inclusive of every parameter that can be quantitated, nor are these indicative of what analysis is required per project and site. Reporting units vary depending on instrument sensitivity and quantitation levels.

The following paragraphs describe Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), Inductively Coupled Plasma Mass Spectrometry (ICPMS), Cold Vapor Atomic Fluorescence Spectrometry (CVAFS) for trace level total mercury and methylmercury.

ICP-AES

These instruments measure characteristic atomic-line emission spectra by optical spectrometry. For this technique a sample aerosol is generated by the use of a nebulizer and is carried into the plasma, and is injected into the ICP subjecting the atoms to high temperatures which results in nearly complete dissociation of molecules. The intensities of the line spectra at specific wavelengths are measured by a photosensitive device. Analysts must carefully evaluate and correct for sources of interferences as discussed in the specific reference methods (US EPA 200.7).

Although the ICP technique may be preferred for some matrices and parameters, other techniques such as Graphite Furnace Atomic Absorption (GFAA) or ICPMS may be required to meet the low detection limits required to meet the water quality standards and/or enforcement limits. Some parameters this may apply to are As, Be, Cd, Pb, Sb, Se and Tl.

ICPMS

The ICPMS instruments are similar in many ways to ICP instruments, except that the ions produced by the high temperatures entrained in the plasma gas are extracted and separated on the basis of their mass-to-charge ratio by a mass spectrometer. As in ICP, there are complex interferences that must be assessed and valid corrections applied (US EPA 6020A). Care also must be taken to prevent problems that can occur due to high dissolved solids concentrations.

CVAFS

Both trace level analysis of total mercury and methylmercury require significant steps be taken by both sampling and laboratory personnel to prevent (and evaluate) contamination since the reporting levels are at sub nano gram per liter concentrations. This includes using specially cleaned containers and collecting field QC samples (US EPA 1631E, US EPA 1630 and US EPA 1669).

Laboratories certified to analyze samples must meet the contamination control requirements in the analytical method so that the integrity of the results produced are not compromised.

Trace level Mercury (Total)

In this method, once the water sample is preserved with dilute HCl, digested with BrCl (and often UV irradiation), the dissolved Hg(II) is reduced with SnCl to volatile Hg(O) which is purged from solution and trapped on gold traps. These traps are heated to desorb the Hg into an inert gas stream that carries the Hg into a cell of a cold vapor atomic fluorescence spectrometer (US EPA 1631E).

Methylmercury

Aqueous samples for methylmercury analysis are preserved with HCl and then distilled. The distillate is ethylated and the methylethyl mercury is separated and carried onto a graphitic carbon trap which is then heated to thermally desorb it from the trap and carried to a pyrolytic decomposition column. Here the organo mercury forms are converted to elemental mercury which is delivered to the cold-vapor atomic fluorescence spectrometer (CVAFS) for detection (US EPA 1630).

The ease of contaminating of ambient water samples for trace level mercury and methylmercury is discussed at length in the applicable reference methods. These methods require detections at the sub nano gram per liter level. If results are required in dissolved samples, it is recommended that filtering is done in the laboratory for these parameters.

C.3. ORGANIC COMPOUNDS

The list of applicable preparation and analytical methods is extensive. Therefore some of the typical techniques used for fuel, process chemicals, and explosives residues are discussed in general terms below, and is not meant to be all inclusive of the techniques available for preparation and analysis of organic compounds. As with any analysis, sample containers and preservation are specific for the matrices and parameters of interest.

Sample Preparation

These are brief descriptions of some techniques applicable to aqueous samples. To prepare aqueous samples, there are specifically approved methods depending on which analytical methods are used. One technique utilizes solvents that will allow extraction of specific compounds; another technique is to use specific solid sorbent materials that will allow for the extraction of specific compounds which are then eluted from the material using solvents. Samples that are 'product' or oil samples may only require solvent dilution as the preparation technique.

Purge and Trap Gas Chromatography (GC)

In these methods, calibration standards are carried through the entire analytical procedure (samples and standards are purged and analyzed exactly the same way). All chromatographic processes achieve separation by passing a mobile phase over a stationary phase. Compounds are separated because they partition differently between the mobile and stationary phases and thus have different retention times. This also applies to High Performance Liquid Chromatography – which is a different technique and is not specifically discussed here.

There are multiple types of detectors used in GC analysis, depending on the method. Some apply to aromatic hydrocarbons, or halogenated organics (chlorinated), or nitrogen and phosphorus containing compounds, etc. A mass spectrometer detector (GCMS) may be applicable to many compound classes, since these are detected on their mass to charge ratio.

GCMS

Analysis by GCMS techniques apply to both volatiles (VOC) and semi-volatile organic compounds (SVOC). Depending on the compound class, the mass spectrometer is tuned using that specific method procedure and criteria. The spectra of each unknown compound is compared to a known target compound and integration is specific to the ion abundances. MS methods always use internal standard calibration techniques. There can be many complications with this type of analysis, therefore chemists with the proper experience and training are essential (US EPA 8000C).