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REPORT

A spatial evaluation of historic iron mining impacts on current impaired waters in Lake Superior's Mesabi Range

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Abstract This paper examines the water quality legacies of historic and current iron mining in the Mesabi Range, the most productive iron range in the history of North America, producing more than 42% of the world's iron ore in the 1950s. Between 1893 and 2016, 3.5×10^9 t of iron ore were shipped from the Mesabi Range to steel plants throughout the world. We map historic sites and quantities of iron mining, ore processing, water use, and tailings deposition within subwatershed boundaries. We then map the locations of impaired lakes within HUC-12 subwatershed boundaries within the Mesabi Range, using government datasets created for US federal Clean Water Act reporting. Comparing watersheds with and without historic mining activity, watersheds with historic mining activity currently contain a greater percentage of impaired lakes than control watersheds within the same range. These results suggest that historic iron ore mining and processing in the Mesabi Range affected water quality on a landscape scale, and these legacies persist long after the mines have closed. This paper outlines a novel spatial approach that land managers and policy makers can apply to other landscapes to assess the effects of past mining activity on watershed health.

Keywords Environmental history · Geospatial analysis · Historical geographic information systems (HGIS) · Historical mining · Iron mining

INTRODUCTION

Water contamination concerns accompany current heavy metal and coal mines across the globe (Cherry et al. 2001; Johnson and Hallberg 2005; Bernhardt et al. 2012; Byrne et al. 2012; McGarvey and Johnston 2013). Pollutant discharge from mine wastes highlights the complex physical character these pollutants possess as they move from ground-based to water or airborne contaminants. The latter types, categorized as secondary or tertiary contamination, are the most challenging to manage and pose the greatest threat to human health (Moore and Luoma 1990). Mine pollutants have the potential to alter the geochemistry of watersheds, especially when they are disturbed by hydrological activity such as flooding, which can produce a massive footprint of toxic legacies (Hunerlach et al. 1999; Grosbois et al. 2012; Moore and Langer 2012). Fluvial transport of mine waste through watersheds and the spread of heavy metal contaminants from abandoned mine sites and waste dumps remain pressing global concerns (Macklin et al. 1997; Miller 1997; MacKenzie and Pulford 2002; James and Marcus 2006; Angelstam et al. 2013; Singer et al. 2013; Keeling and Sandlos 2015).

Mines can alter geomorphic systems and hydrological cycles during their operation and abandonment, dewatering, ore processing, and post-mining flooding (Younger and Wolkersdorfer 2004; Savage et al. 2010; Ross et al. 2016). Mine-pit lakes have emerged as a recent focus of water quality concern. When subsurface and open-pit mines are closed, the dewatering pumps are typically stopped. Groundwater then floods these former mines, creating mine-pit lakes which can be contaminated with a variety of heavy metals (Axler et al. 1996, 1998). Additionally, some mining sites, including some within the Mesabi Range such as the Dunka mine, contain metal sulfides such as pyrites in the surrounding rock and overburden. After those mines have been abandoned and pumping has stopped, exposure of the sulfides to air and water can create acidic drainage which decreases stream pH and may also release lead, arsenic, aluminum, manganese, and nickel into watersheds. Such sites can require perpetual care (Pellicori et al. 2005; LeCain 2009).

Ore processing, not just mining, also has the potential to impact watersheds, most notably from the disposal into surface waters of tailings, a finely ground form of mine waste. Tailings can damage fisheries, affect downstream agriculture, and mobilize toxic chemicals into community water sources (Quivik 1998; Sullivan 2014; Manuel 2015).

Since the 1977 Surface Mining and Reclamation Act, mining companies have been required to reclaim US mine sites when production stops. Those efforts are effective at removing debris and revegetating sites, but less effective at halting acid drainage. Landscape-scale impacts produced from mining, both chemical and physical, may resist reclamation efforts, leading to the slow regrowth of vegetation on reclaimed mine lands and tailings piles (LeClerc and Wiersma 2017). Additionally, no federal law requires remediation of mines closed before 1977, and those mines, processing facilities, and tailings piles continue to release pollutants into watersheds. Legacy pollutants from mines abandoned before 1977 may persist within river, steam, and lake sediments (Limerick et al. 2005; Worrall et al. 2009; Bird 2016).

Studies of historic mining impacts on current environmental condition have typically focused on contaminated sediments located downstream of copper, silver, and gold mining and ore processing sites (Hudson-Edwards et al. 1997; Thomas et al. 2002; Church et al. 2007; Haunch and MacDonald 2011; Haunch 2013; Walker et al. 2015). Fewer studies have examined the historic water quality legacies of iron mining, which has been portrayed as less toxic because cyanide and mercury were not used in processing (Langston 2017). Yet the mining and processing of iron ores in the Lake Superior region have produced environmental problems including acid mine drainage when pyrites were present, the release of asbestiform fibers from some taconite tailings, and the production of atmospheric mercury from taconite beneficiation (Langston 2017).

This paper uses methodologies found commonly within the discipline of historical GIS such as spatializing historical documents, record linking across datasets, and comparing historical environments and landscapes to modern ones (Cunfer 2008; Gutmann et al. 2016; Van Allen and Lafreniere 2016; Clifford 2017). We extend these disciplinary approaches by using historical sources to understand the past and to inform present day understandings of mining impacts on the environment. We also suggest two policy changes to improve water quality monitoring in the mining region.

Using publicly available water quality databases from the Minnesota Pollution Control Agency and historical mining datasets derived from archives, this paper analyzes the impacts that past iron mining has had on the watersheds of Lake Superior's Mesabi Range, asking whether the influence of historic iron mining on water quality can still be detected today. We ask if watersheds with historic mining activity have different water qualities than watersheds without historic mining activity, and if those effects differ by mining technology. Finally, we present a novel historical and spatial approach that can be applied to other landscapes to assess the impacts that mining has had on watersheds, suggesting that historical datasets can be used to inform current environmental science and policy.

THE MESABI RANGE

The Mesabi Range, North America's most productive iron mining district, stretches across the upper reaches of two major watersheds. The first watershed is the St. Louis River flowing into Lake Superior, the world's largest lake by surface area and headwaters of the Great Lakes, which contain 21% of the world's freshwater (MacFarlane 2016). The second watershed contains the headwaters of the Mississippi River, North America's largest drainage basin (Fig. 1). More than 400 mines operated on the Mesabi Range after 1893, producing more than 3.5×10^9 t of iron ore (Baeten et al. 2016). Each of these mines had the potential to affect water quality, yet as mining technologies shifted, the potential impact of iron mining and processing may have shifted as well. The iron mines of the Mesabi Range and the broader Lake Superior Iron Ore District were globally significant, serving as the primary producer of global iron ore for more than a half-century, and providing nearly half the world's supply of iron ore during the years following World War II (Forbes 1953). But as these Lake Superior ore bodies became depleted and iron mines developed elsewhere, the global contribution of the region declined. Today, the Mesabi Range still accounts for nearly 99% of United States iron production, but only 2% of global production, a marked decline that became pronounced in the 1980s (Yellishetty et al. 2010). While reclamation efforts concerned with rehabilitating the post-mining landscape have removed much of the mining infrastructure (such as processing plants) from the landscape, potentially toxic legacies of mining remain in tailings ponds, mine-waste dumps, and lake beds.

Mining technologies

Direct shipping ore mines 1893–1970s

The focus of metal mining is the profitable extraction of ore, an economic term used to describe a metalliferous

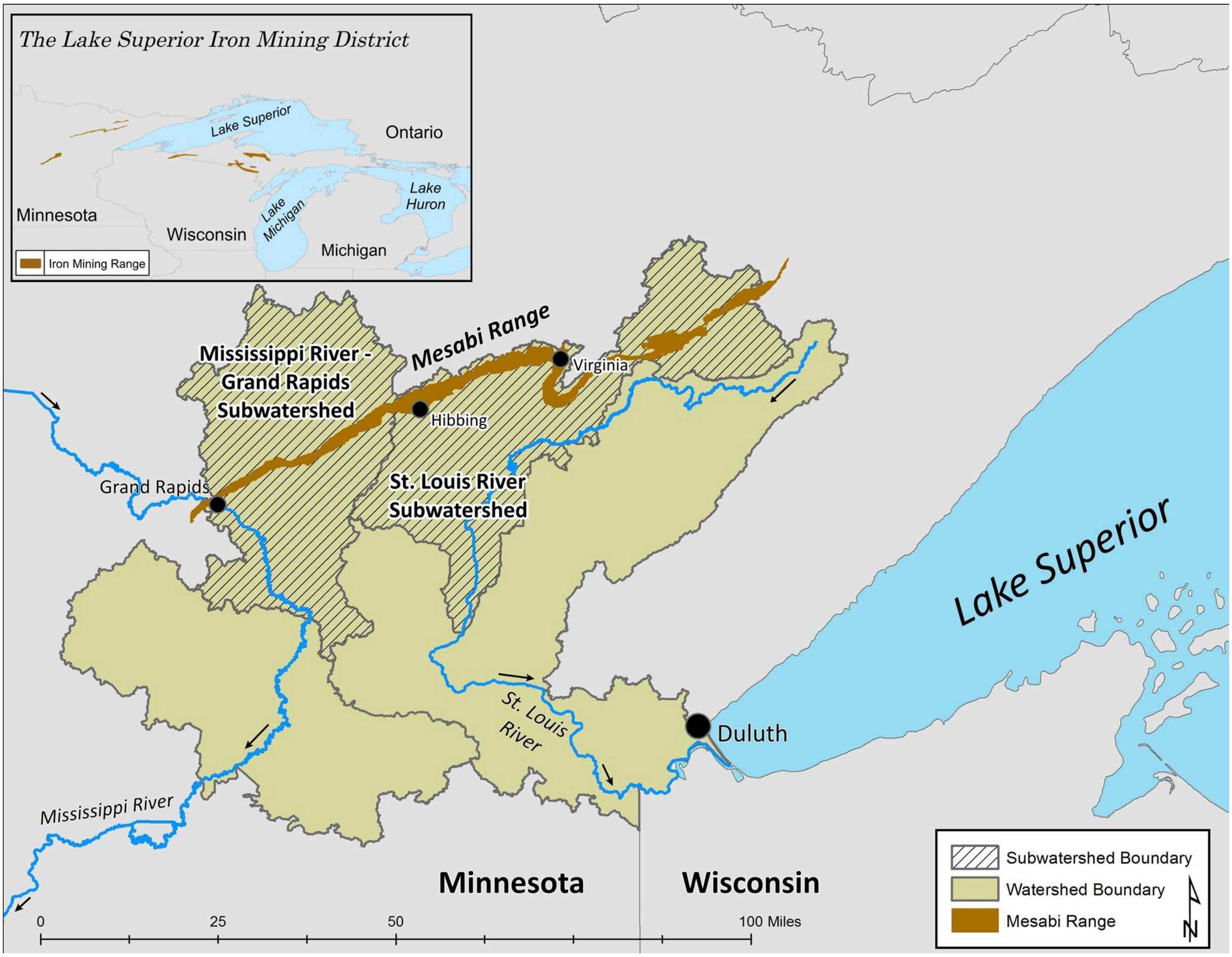

Fig. 1 Watersheds (HUC-08) of the Mesabi Iron Range. The subwatersheds (HUC-10) are those portions of the watersheds located within the mining region

deposit. In the Mesabi Range, three types of ore were mined: direct shipping ore, washable ore, and taconite (Taggart 1927). Beginning in 1893, iron mines on the Mesabi Range targeted rich deposits of hematite iron ore, mineral bodies containing upwards of 70% iron (Davis 1964). These high-grade deposits contained what were called direct shipping ores that could be dug from the earth, loaded onto a rail system, and shipped directly to the lower Great Lakes for smelting. Direct shipping ore mining in the Mesabi Range involved both underground and open-pit mines. Both types of mines filled with water when the elevation of the active mine dropped below groundwater elevation, which meant that engineers needed to dewater the mines with pumps and discharge the effluent into neighboring streams and lakes. Dewatering a mine had several possible effects on water quality (Zellie 2005). Mine dewatering might lower the water table in the local area, which could dry up some small streams. Mine dewatering also created effluent discharges that could be contaminated with heavy metals and industrial refuse from the mining process.

Deforestation associated with the mining of direct shipping ores also had the potential to affect water quality. Underground mines required timbers to support subterranean workings; open-pit mines required clearing at the local site, and railway construction required harvests of local forests for crossties. Construction of open-pit direct shipping ore mines required the removal of overburden, consisting of all vegetation on the site and up to 132 m of soil and rock (Young 1932). No state laws required restoration of such sites until 1969, so the deforestation and soil disturbance produced from direct shipping ore mines likely led to increased runoff and siltation into waterbodies (Mineland Reclamation: Minnesota's Program 1988).

Washable Ores 1910–1980s

Mesabi Range low-grade iron ore mining began in 1910, with the extraction and processing of silica-laden deposits called washable ores (Van Barneveld 1913). Washable ores contained about 40% iron upon extraction, a percentage of iron that was too low to send directly to smelters. Washable ore mines were primarily open-pit excavations, a mining method commonly employed for the extraction of lower-grade ores (Young 1932). To create a merchantable product, before shipping, mining companies needed to increase the percentage of iron in these washable ores, achieved through a process called beneficiation. Mining companies constructed beneficiation plants at a distance of up to 8 km from the mine and used mechanical processes to separate the waste from the ore and concentrate the iron content.

In the process, beneficiation plants consumed on average 3400 L of water and created on average 1.5 metric tonnes of tailings for each metric tonne of iron produced (Baeten et al. 2016). Washable ore beneficiation plants depended on local surface water sources for two main purposes. First, the surface waters themselves were essential for iron ore concentration, and second, surface waters provided mining companies with a sink to deposit the continual flow of tailings produced during ore concentration. Throughout the beneficiation process, water was introduced to the ore as it traveled across screens and classifiers, riffled tables, and through mechanisms designed to capture heavy material and release the less dense and lighter material as tailings.

Owing to their need for water, mining companies constructed these beneficiation plants near lakes, from which they drew water to use for ore concentration. For a low-grade ore mine to be profitable, an ample supply of water was nearly as important as a plentiful ore deposit. The smallest of washable ore beneficiation plants required a constant water supply of "at least 1200 gallons of water per minute" [4542 L], while larger plants required significantly more water (Iron Ore Concentrating Plants of Minnesota 1920). Water helped the material move through the beneficiation facility, aided in separating the ore from the mineral waste, and ultimately transported tailings to deposition sites, which were initially lakes and later constructed tailings basins (Hubbard 1948).

Taconite processing 1956–2016

Beginning in 1956, the focus of mining companies in the Mesabi Range shifted to an even lower grade of iron ore called taconite. A magnetite ore, taconite contained between 15 and 30% iron, the lowest percentage of iron and the highest percent of waste among Mesabi Range ores. Beneficiation of these ores occurred at taconite concentrators, where ore was crushed and finely ground. During taconite concentration, water was introduced to the ore to separate out waste and limit the quantity of dust produced (Kohn and Specht 1958). Next, the slurry of magnetite, water, and waste was fed into magnetic separators and gravity classifiers, where magnets attracted the iron while the water and tailings continued to travel through the facility (Davis 1964). After magnetic concentration, the taconite concentrates were dewatered and dried, then combined with clay to create small spherical pellets (Hunt 1951). The tailings produced from taconite ores, like those produced from washable ores, were pumped away from the processing plants and deposited either back into lakes or into constructed tailings basins. However, due to the more intensive processing that occurred at taconite concentrators, taconite tailings were much finer than washable ore tailings, allowing for easier mobilization within waterbodies. Each metric tonne of taconite pellets shipped off the range resulted in the production of three tonnes of tailings and the consumption of 22 700 L of water (Cummins and Given 1973; Technical Resource Document: Extraction and Beneficiation of Ores and Minerals 1994).

MATERIALS AND METHODS

Mapping watershed boundaries

This study's analysis of iron mining's impacts on the watersheds of the Mesabi Range began with locating the boundaries of HUC-12 subwatersheds. The US Geological Survey (USGS) uses Hydrological Unit Codes (HUC) to delineate watershed boundaries (Seaber and Knapp 1994). Hydrologic Unit Codes range from 2 to 12-digits, and the smaller the HUC code digit, the larger the watershed. The national Watershed Boundary Dataset (WBD) provided by the USDA Geospatial Data Gateway was accessed for this analysis, and individual watersheds delineated by the Minnesota Department of Natural Resources were identified and isolated (The 8, 10, and 12 hydrologic unit boundaries for Minnesota 2008; Watershed Boundary Dataset (WBD)). The HUC-12 scale was used because it allowed enough spatial resolution to distinguish between watersheds with differing levels of historic mining and processing activity. The intensity of mining that occurred within each HUC-12 that surrounded the Mesabi Range was quantified by calculating the tonnes of direct shipping ore mined, tonnes of washable ore mined and processed, tonnes of taconite ore mined and processed, tonnes of tailings deposited, and gallons of water consumed by processing plants (Baeten et al. 2016).

Mining in the Mesabi Range was confined to the Upper Mississippi-Grand Rapids and St. Louis River watersheds, in which each contains smaller HUC-12 subwatersheds, ranging in size from 10 000 to 40 000 acres. A subset of HUC-12 subwatersheds that were located within stream reaches of mining activity from the Mesabi Range were selected for analysis consisting of 25 HUC-12 subwatersheds in the Upper Mississippi Grand Rapids watershed, and 26 in the St. Louis River watershed. Mining activity in the Mesabi Range was confined to 21 of the HUC-12 subwatersheds, while the remaining 30 functioned as units for the analysis. These 51 HUC-12 subwatersheds were isolated in a historical GIS (HGIS) and their boundaries were used as the geographic basis for the analysis of mining impacts (see Fig. 2).

The location of mine-pit lakes within each HUC-12 subwatershed of the study area was also identified. Mine-pit lakes are historical mines that were abandoned and allowed to fill with water, ranging in size from 1 to 1055 acres. Hydrological datasets managed by the Minnesota Department of Natural Resources were used to identify and isolate the former mine-pit lakes from naturally occurring surface waters.

Mapping mining intensity

The sites of all iron mines and processing plants and the visible extent of mine waste were mapped to quantify the level of historic mining intensity within each HUC-12. Mine locational data were acquired in a shapefile format from government-managed geospatial clearinghouses, such as the USGS (Mineral Resources Data System 2005). The analysis of both aerial imagery and LiDAR data (1-m digital elevation models) provided by the Minnesota Department of Natural Resources was used to populate the waste footprint (LiDAR Elevation, Arrowhead Region, NE Minnesota 2011; LiDAR Elevation, Central Lakes Region, Minnesota 2012). The visible waste footprint, which

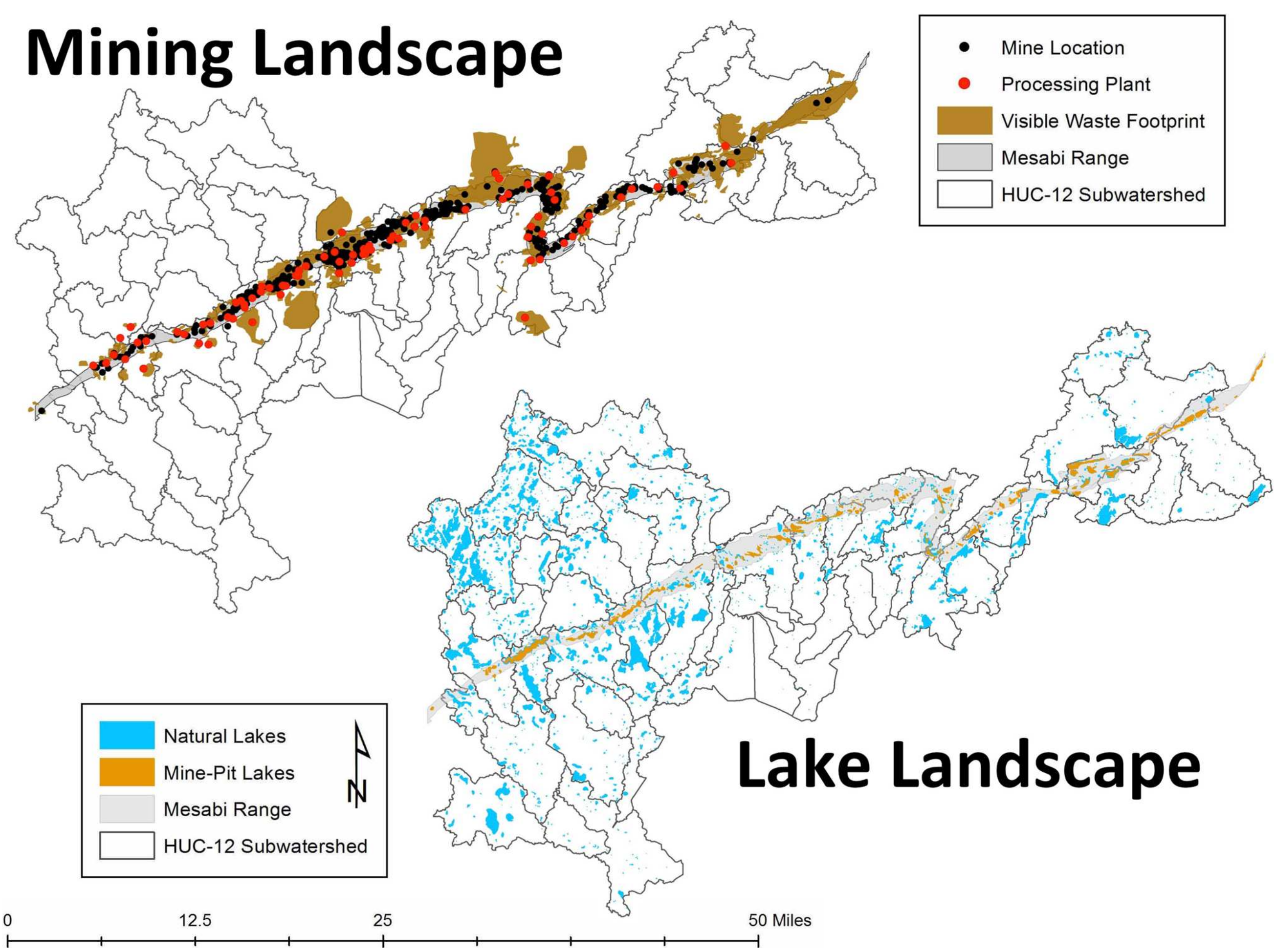

Fig. 2 Overview of the mining landscape (mine locations, processing plants, and visible waste footprint) and lake landscape within HUC-12 subwatersheds

includes open-pit mines, tailings piles, and mine waste, was manually digitized and the total area calculated, creating a dataset that represents the current extent of barren lands associated with past mining activity.

To calculate the quantities of ore mined, waste produced, and water consumed over the history of each mine and processing plant, annual iron ore shipment statistics were entered into our HGIS. These data were recorded by mines and published in trade journals and archives. Mine production statistics from a 114-year period (5972 entries from 1898 to 2012) were entered into the HGIS (Table 1) (The Lake Superior District 1920). Each mine was then coded as one of the three types of ore extracted: direct shipping ore, washable ore, or taconite.

To quantify water consumption and tailings production for each HUC-12 subwastershed, the locations of beneficiation facilities were located, mapped, and linked to source mines. This process required the analysis of archival records, historic maps, and aerial imagery, together, to determine the locations of beneficiation facilities, the companies that operated them, and the years of operation. The data were manually geocoded and record linked within the HGIS, providing the locations of both mines and processing plants, as well as iron ore production totals from direct shipping ore mines, washable ore mines, and taconite mines, for every year from 1898 to 2012.

Table 1 Source materials used in constructing the HGIS

Archival source	Historic mine production data	Year
Iron trade review	2550 annual production entries	1898–1930
Steel	913 annual production entries	1931–1944
Skillings' mining review	2440 annual production entries	1944–1981
Mining tax guide (MN Dept. revenue)	69 annual production entries	2011/2015
Archival sources	**Beneficiation plant locational data**	**Years**
Historical trade journals/maps/USGS mineral reports	88 beneficiation plant shapefile points	1910–1980
Government database	Geospatial data	Type
USGS mineral resource data system	403 shapefile polygons	Mine locational data
USDA geospatial data gateway	3901 shapefile polygons	Watershed boundary dataset: HUC-12
Minnesota geospatial commons: Minnesota pollution control agency	3840 shapefile polygons	Impaired waters data: lakes

To determine water usage and tailings production, concentration ratios were then calculated using archival sources, such as the *Iron Trade and Review*, a trade journal containing annual production reports from iron ore concentrators. Because water acquisition was essential at beneficiation plants, companies tracked the quantity of water consumed in different stages of production, allowing the calculation of average water consumption and tailings production during beneficiation for washable ore versus taconite processing. On average, washable ore processing plants consumed 3400 L of water for every tonne of ore processed, while taconite processing plants consumed on average 20 000 L (Taggart 1927). Washable ores processing plants produced on average 1.4 tonnes of tailings for every tonne of washable ore concentrates produced, while taconite plants produced on average 2.7 tonnes of tailings for every tonne of taconite concentrates produced. The increase in water consumption and tailings production seen at taconite beneficiation plants was due to the physical differences between taconite ores and washable ores. Taconite ores required much more intensive processing, due to both their lower concentration of iron, and the compact nature of the mineral deposit (Davis 1964). This meant that compared to washable ores, which underwent a relatively simple classification process during concentration, taconite ores were subjected to a much more intensive beneficiation process, including crushing and fine grinding, which required more water and also produced more tailings. This more intensive beneficiation process made taconite tailings much finer than washable ore tailings, which allowed taconite tailings to migrate more easily and at further distances than washable ore tailings (Baeten et al. 2016).

To calculate the average amount of tailings produced and water consumed during iron ore concentration at individual processing plants, the ore production totals from mines that produced low-grade ores were record linked to the beneficiation plants where the ore was concentrated. These production totals were then entered into these concentration formulas to generate annual water consumption and tailings production from each beneficiation plant. For instance, the Quinn-Harrison washable ore concentrator in the Mesabi Range processed 15 million tonnes of washable ore in 1925. Assuming that this washable ore concentrator consumed 3400 L of water for every tonne of ore processed, this plant would have consumed 51×10^9 L of water in 1925 alone.

To calculate mining intensity within each HUC-12 subwatershed, the mapped locations of mines, beneficiation plants, water withdrawals, and tailing production were spatially joined and aggregated to each individual HUC-12 subwatershed for each year of mining activity. This provided the total tonnes of direct shipping ore, washable ore, and taconite mined, as well as the total tonnes of washable ore concentrated, and the total tonnes of taconite ore concentrated at beneficiation plants for each watershed during each year. For each HUC-12 subwatershed, the total amount of tailings produced and water consumed from both washable ore and taconite ore beneficiation plants were calculated annually for the years 1910–2012. The quantities of ore mined in each subwatershed, the types of mining technology employed, the quantity of tailings deposited, and water used can be seen in the choropleth maps in Figs. 3 and 4.

Categorizing impaired waters versus non-impaired waters

The MPCA estimates that about 40% of Minnesota's waters (including lakes and streams) fail to meet water quality standards outlined by the Clean Water Act (Minnesota's Impaired Waters List 2017). Many factors influence water quality, including agricultural runoff, combined sewage overflows from some municipalities, and impermeable surfaces in developed areas. Agriculture in the state is a particularly important source of water quality concerns. However, within northeastern Minnesota where the Mesabi Range is located, agriculture and urban development are less significant than in other parts of the state, primarily because populations are lower and large agricultural operations are rare in this part of the state due to the climate, soil, and topography (Minnesota Pollution Control Agency 2008).

As part of the state's Clean Water Act reporting, the MPCA assesses the water quality of a certain fraction of stream reaches and lakes within Minnesota. The Clean Water Act defines a water body as impaired if it fails to meet a water quality standard set by the state, usually related to a beneficial use such as swimming, drinking, or fishing (Water Quality Standards 2017). MPCA staff, agency partners, and volunteers collect environmental data on selected lakes and streams across the state over a 10-year period (Anderson et al. 2014; Anderson 2016). Beginning in 2008, the MPCA introduced a watershed approach, assessing lake and stream chemistry and biology within eight of the state's 80 major watersheds per year, so that each watershed will be assessed once a decade (Anderson and Martin 2015). The MPCA aimed to monitor and assess all lakes larger than 500 acres and at least half the smaller lakes (Lakes and Water Quality 2017).

MPCA scientists, in collaboration with state and federal agency personnel, collect water samples from individual waterbodies, called "assessment units," which consist of stream reaches, lakes, and wetlands (Anderson 2016). Samples are assessed for physical, chemical, and biological parameters including fish bioassessments, macroinvertebrates, turbidity, mercury, total phosphorus, PCBs and other synthetic chemicals, fecal coliform, and low dissolved oxygen. No stream reach or lake in the Mesabi Range had sufficient data to assess all these parameters, however. For example, for 34 stream reaches in our sample, 21 possible parameters were listed, but 82% of them were not assessed or had insufficient data for the state to report the data. In addition to reporting on individual water quality measures, the MPCA staff create a single category for each water body or stream reach assessed: healthy, possibly healthy, or impaired. Because of missing data, not a single stream reach or lake in the Mesabi Range has been categorized as "healthy." Instead, most have been categorized as either "impaired" (when some measured parameters fail to meet standards) versus "possibly healthy," which is used when measured parameters meet standards, but some key parameters were not measured (Water Quality: Describing Water Quality 2017).

Gaps in the data on individual water quality parameters meant that this study had to rely upon the MPCA's summary categories for each waterbody (Impaired Lakes 2012). The MPCA has assessed 40% of the total lake acreage within the Mesabi Range itself. Because of the agency's emphasis upon larger lakes, only 15% of lakes within the Mesabi Range have been included in that assessment. Of 251 lakes created by former mine pits, only 5% have been included in the assessment. Choropleth maps were used to identify the spatial variation in the proportion of impaired lakes, and the location of historic mining intensity, within each HUC-12 subwatershed across the study area.

Within the 51 HUC-12 subwatersheds in this study's analysis area, 2509 lakes have been identified totaling 28 707 ha of lake surface area. The MPCA assessed 187 of these lakes, categorizing 110 of them as impaired (9607 ha) and 77 (3793 ha) as possibly healthy (i.e., no impairments of beneficial uses, but not all uses assessed). This study excluded the other 2322 lakes that had not been assessed (mostly lakes smaller than 1 ha), and those that did not contain sufficient data for the MPCA to categorize as impaired or possibly healthy. Within each HUC-12 subwatershed, the acreage, location, and water quality condition category of each assessed lake were recorded. Then, for each HUC-12 subwatershed, the total acreages of lakes that were categorized by the MPCA as "possibly healthy" versus "impaired" were summed and the proportion of impaired lake acreage calculated (Impaired Lakes 2012). The presence or absence of each type of historic mining was then recorded for each HUC-12 subwatershed. The proportion of impaired waters in HUC-12 subwatersheds with historic mining were compared to HUC-12 subwatersheds without historic mining, using Student t-tests.

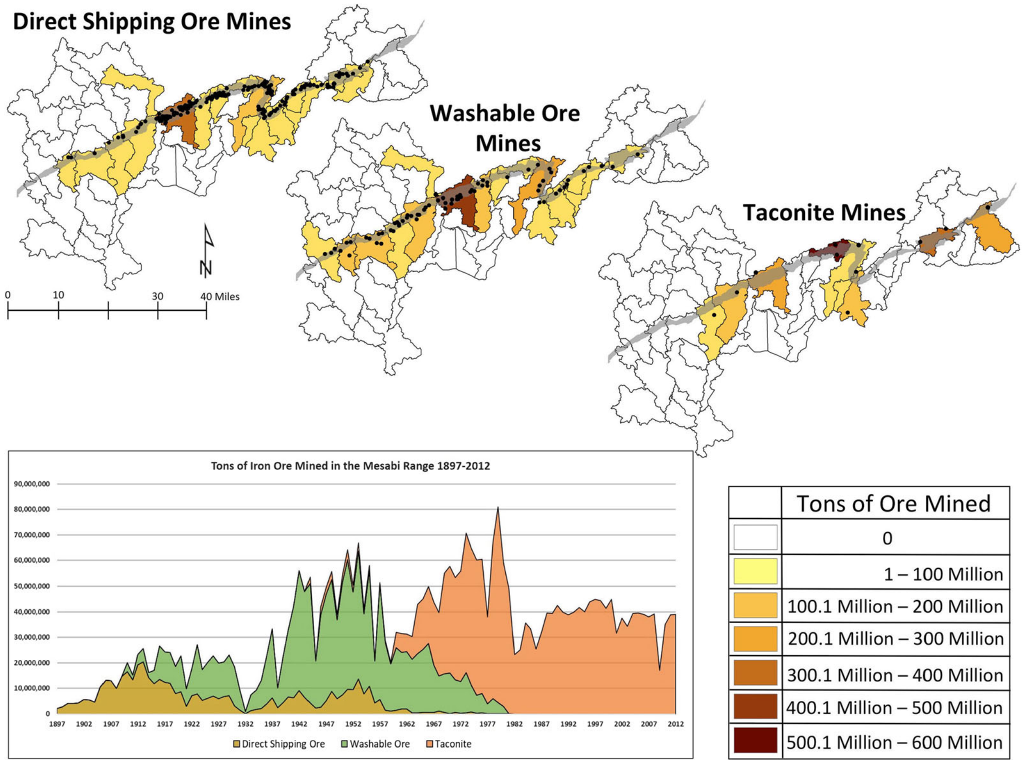

Fig. 3 Choropleth map showing the intensity of mining (100-million-tonne intervals) within the HUC-12 subwatersheds as produced by a specific mining technology from 1898 to 2012

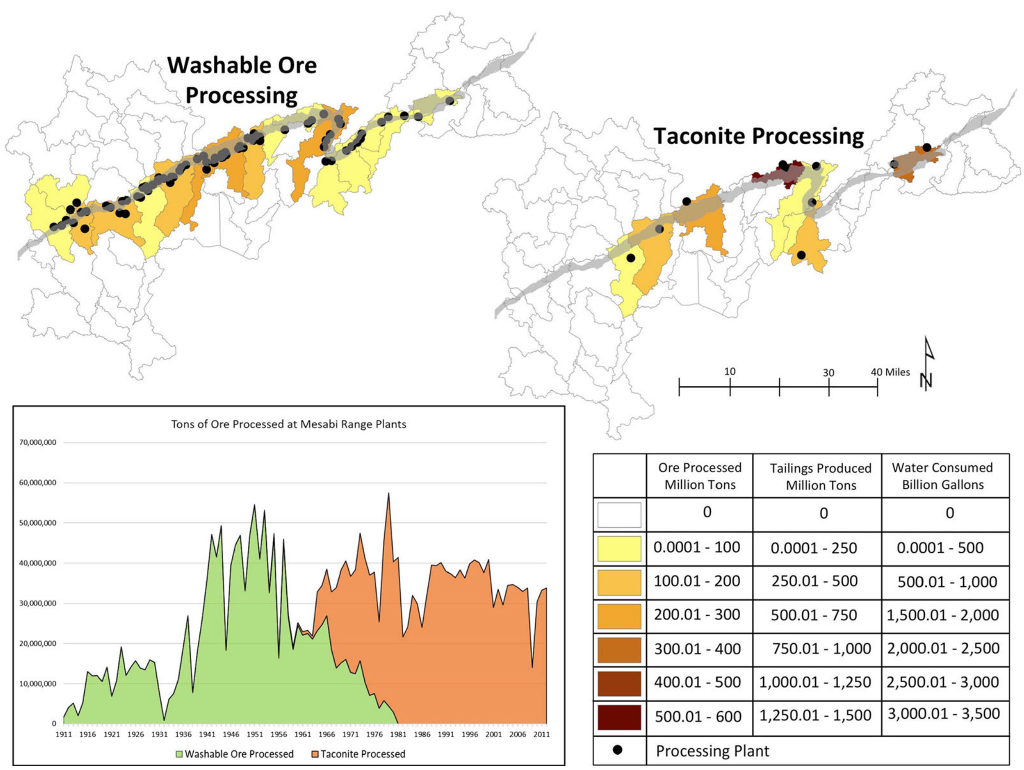

Fig. 4 Intensity of washable ore processing and taconite processing within the HUC-12 Subwatersheds

RESULTS

Historic mining and ore processing were concentrated in 20 of the 51 HUC-12 subwatersheds across the Mesabi Range (Fig. 2). Waste from mining, however, is present in 29 of 51 HUC-12 subwatersheds, demonstrating that the waste footprint is larger than the mine and processing plant locations would suggest. Within the immediate extent of the Mesabi Range's iron formation, 137 natural lakes now exist (643 ha), compared to 251 mine-pit lakes (4228 ha) (Fig. 2). 87% of lake acreage within the Mesabi Range consists of former mine pits, rather than natural lakes.

Over the 114 years of the study sample, direct shipping ores were mined in 17 of the HUC-12 subwatersheds, while washable ores were mined in 16 subwatersheds, and taconite ores in 9 subwatersheds (Fig. 3). More than one type of mining technology occurred in 15 of the 20 subwatershed that experienced mining activity. HUC-12 subwatersheds where direct shipping ore mining occurred averaged a tonnage of 48.9 million tonnes per watershed, while those that experienced washable ore mining averaged 85.7 million tonnes, and HUC-12 subwatersheds that experienced taconite mining average 186.3 million tonnes. Although taconite mines produced the largest average of ore mined per individual watershed and the largest total tonnage of the three mining technologies, taconite mines were located in the fewest watersheds, suggesting that taconite mining had more concentrated impacts.

Water consumption and tailings by different mining types are mapped in Fig. 4. The extent of washable ores processing was more widespread than taconite processing, occurring in more watersheds and at nearly ten times as many processing plants. The intensity of water withdrawals and tailings disposals into watersheds from taconite beneficiation was more intensive than that at washable ore plants.

The percentage of impaired lake acreage within each individual HUC-12 subwatershed and the intensity of different mining technologies are shown in Fig. 5. HUC-12 subwatersheds that are located within the immediate extent of the Mesabi Range have a higher percent of impaired lake acreage than the units located outside of the Mesabi Range. Similarly, watersheds with greater historic mining intensity coincide spatially with greater proportion of impaired waters.

The intensity of ore processing as it compares to impaired lake acreage is mapped in Fig. 6. HUC-12 subwatersheds with greater historic ore processing show a greater proportion of impaired waters.

HUC-12 subwatersheds with a history of direct shipping ore mining have a higher proportion of impaired lakes than watersheds without a history of mining (Table 2, $t(36) = 2.05$, $p < 0.05$). Because six HUC-12 subwatersheds with historic direct shipping ore mining also contain modern taconite mining, the analysis was repeated using only those HUC-12 subwatersheds without modern taconite mining to control for possible effects of modern mining on water quality. The effect for direct shipping ore mining remained, although with the smaller sample size, the effect was not quite significant at the $p < 0.05$ level, with $t(30) = 2.00$, $p = 0.055$.

HUC-12 subwatersheds with a history of washable ore and taconite mining and processing also have a higher proportion of impaired lakes than those without such mining, but these relationships are not statistically significant (Table 2). However, several of the HUC-12 subwatersheds that experienced the greatest intensity of both washable ore and taconite mining and processing were also watersheds where no lakes were assessed for water quality, making it difficult to evaluate these results (Figs. 5 and 6).

DISCUSSION

This study asks: Do environmental impacts from historic iron mining in the Mesabi Range persist? Mapping historic mining and current lake water quality within the Mesabi Iron Range suggests that they do. HUC-12 subwatersheds that experienced historical mining activity are also the subwatersheds with a greater percentage of impaired lake acreage. These results suggest that historical iron ore mining may have influenced water quality in the Mesabi Range on a landscape scale, and that those legacies may persist after the mines and processing plants have closed.

Because the locations of high-grade and low-grade ore mining overlapped across the Mesabi Range, the possible effects of different types of mining activity produced within some watersheds could not be distinguished. However, relationships between historic mining activity and current water quality persisted even when watersheds that contained recent mining activity were removed from the analysis. This suggests that apparent water quality effects of historic mining activity are unlikely to be an artifact of current mining activity in the same subwatersheds.

Watersheds with recent taconite mining or processing did not contain a statistically significant higher proportion of impaired waters compared to watersheds without taconite activity. However, this does not necessarily mean that taconite mining and processing have protected water quality, because the MPCA has yet to assess many of the lakes in the subwatersheds where the most intensive taconite mining and processing occurred. Additionally, 95% of the mine-pit lakes within the Mesabi Range have not been assessed for water quality by the MPCA. The data limitation in these lake assessments suggests a policy recommendation for the MPCA to include more mine-pit lakes in

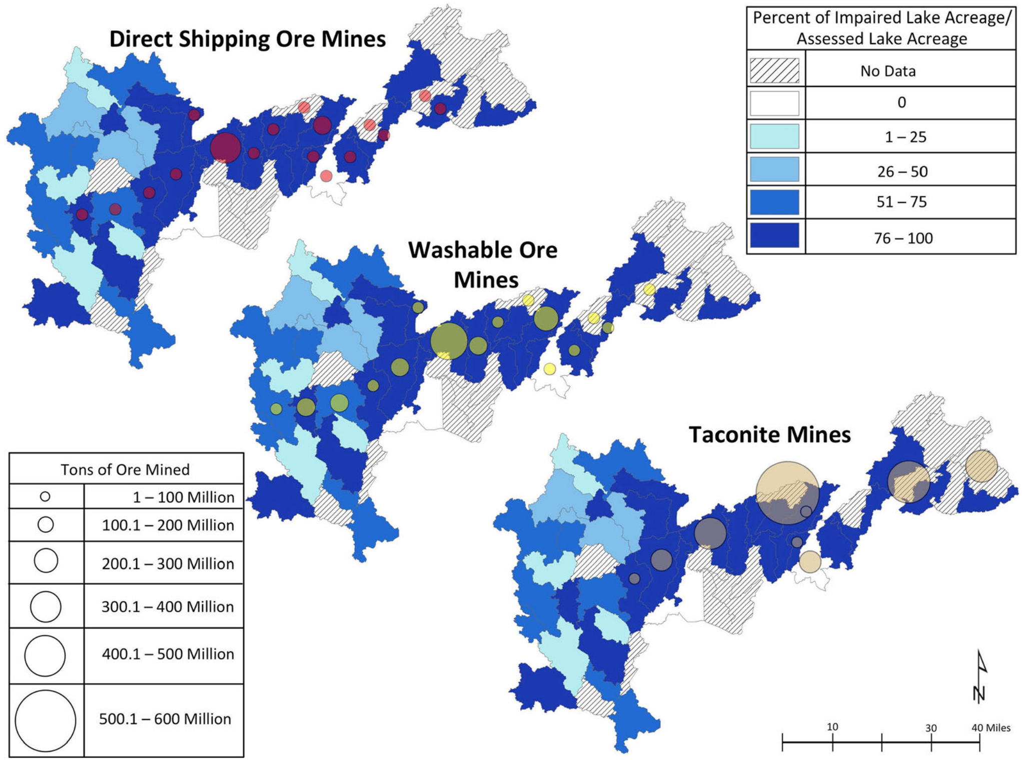

Fig. 5 Percent of impaired lake acreage compared with mining intensity. Graduated symbols represent total tonnes of ore mined within each subwatershed

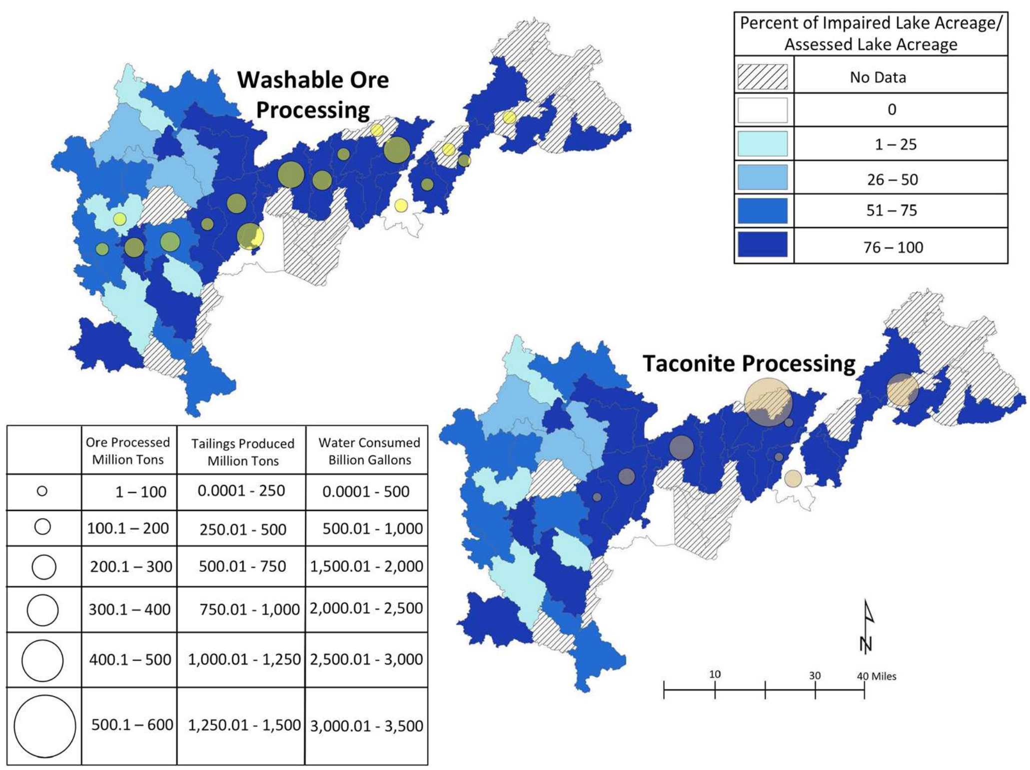

Fig. 6 Percent of impaired lake acreage compared with intensity of ore processing, tailings production, and water consumption. Graduated symbols represent total amount of ore processed within each subwatershed

Table 2 Mean proportion impaired lakes in HUC-12 subwatersheds with different types of historic mining activities

Mining activity	Proportion impaired lakes	SD	*t* test statistic	*p* value
Watershed without direct shipping ore mining $n = 24$	0.63	0.156	$t(36) = 2.05$	0.048
Watershed with direct shipping ore mining $n = 14$	0.863	0.162		
Watershed without washable ore activity $n = 23$	0.665	0.16	$t(36) = 1.1$	0.3
Watershed with washable ore activity $n = 15$	0.794	0.18		
Watershed without taconite activity $n = 32$	0.697	0.126	$t(36) = 0.76$	0.4
Watershed with taconite activity $n = 6$	0.814	0.421		
Watershed without low-grade ore activity $n = 21$	0.633	0.169	$t(36) = 1.64$	0.11
Watershed with low-grade ore activity $n = 17$	0.818	0.156		

water quality assessments and to assess waters within the HUC-12 subwatersheds that experienced taconite activity. Without those data, it is difficult to demonstrate the results of the taconite industry's efforts to protect water quality on a landscape-level scale.

The recreation of the historic waste footprints from aerial imagery and LiDAR data does have some limitations. Only the waste that is visible on the landscape today was able to be identified. The tailings that were deposited into surface waters, reclamation efforts such as re-vegetation, and successive waves of mining have made identifying some surface wastes challenging. Further research using advanced geospatial technologies such as photogrammetry may help identify the locations and quantity of additional historic waste footprints.

Within the Mesabi Range, some HUC-12 subwatersheds without mining had significant proportions of impaired lakes, showing that mining is not the only factor influencing water quality in the region. Nevertheless, within northeastern Minnesota where lake and stream water quality is generally better than in other, more developed parts of the state, the Mesabi Range stands out for its problematic water quality.

In the United States alone, 40% of headwater streams in the western half of the nation are polluted by mining, and more than 19 000 km of rivers are contaminated (Wernstedt and Hersh 2010). Efforts to regulate mine tailings and abandoned mines in the United States have a long and contested history. Across the United States, communities expressed concern about possible water quality impacts of mining as early as the late 19th century, but had few legal tools available to limit pollution (Isenberg 2005; Hanak et al. 2011). The 1872 Mining Law, the first law to govern American mining, did not regulate water usage or tailings disposal, nor did it require reclamation of closed mines. The law's intent was to encourage mining by aiding the transfer of mining rights to private interests, not to regulate pollution (Wernstedt and Hersh 2010).

Federal mining policies that protected water quality were not enacted for another century. In 1972, the U.S. Congress passed amendments to the Federal Water Pollution Control Act (commonly known as the Clean Water Act) which established a regulatory structure for pollutants discharged into American waterways and established water quality standards for surface waters (Langston 2017). In 1974, the U.S. Forest Service began requiring reclamation on Forest Service lands after mines closed, and the Bureau of Land Management followed suit in 1981. The courts found that on public lands, federal and state regulations such as the Clean Water Act applied to mining, but these same regulations did not apply to mines that had been abandoned before the regulations were enacted. The passage of the 1977 Surface Mining Control and Reclamation Act established a program to reclaim mines after closure. However, according to a 1988 General Accountability Office report, approximately 114 000 ha of abandoned or suspended operations have not yet been reclaimed (Surface Mining: Complete Reconciliation of the Abandoned Mine Land Fund Needed 1988).

Within the Lake Superior basin, the most notorious case involving water pollution from iron tailings was the Reserve Mining Company case. In 1947, the State of Minnesota gave permits to Reserve Mining Company allowing the company to dump 400 million tonnes of mining waste directly into Lake Superior. The waste contained asbestiform fibers, which made their way into the drinking water of Duluth, the largest city in the basin. By 1972, Duluth's drinking water contained over a billion fibers of asbestos per liter. Yet the state was unable to restrict the company's dumping of tailings into Lake Superior, and not until the federal government stepped in and took the company to court did the practice end, leaving a legacy of continuing water contamination (Langston 2017).

CONCLUSION

This study aims to understand if the locations and intensity of historic mining activity can help us understand the location of current impaired waters in watersheds. We began by creating an historic GIS from archival data, allowing us to visualize the historic mining landscape within a current watershed. We have previously quantified the visible extent of mine waste in the Mesabi Range, calculating that it covered 25% more hectares than the original iron formation itself (Baeten et al. 2016). Today, there are more than 250 lakes in the Mesabi Range that did not exist in 1890, and of the 4945 ha of lakes located within the Mesabi Range, 87% consist of abandoned mines which have filled with water. Yet few of these mine-pit lakes have been assessed by the MPCA for water quality. Additionally, the environmental impacts from mining can migrate far from the mining footprint, mobilizing into watersheds beyond the direct reaches of the mines.

Since the 1970s, regulatory efforts across the globe to improve water quality in mining regions have led to substantial improvements in current mining operations, but problems from historic and current iron mining persist (Muskie 1972). In the Rio Tinto region of Spain, more than 5000 years of mining for iron as well as copper and manganese have produced legacy pollutants (Braungardt et al. 2003; Hudson-Edwards 2016). Tailings disasters have been common at abandoned and operating mines. On November 5, 2015, a tailings dam located near the town of Bento Rodrigues in southeast Brazil ruptured, sending roughly 60 million cubic meters of iron ore tailings into the Doce River Valley, killing 19 people. The tailings traveled more than 450 km until reaching the Atlantic Ocean. Although Samarco, the mining company in charge of the dam, claimed that these iron ore tailings were an inert mixture of water, silica, and clay, a United Nations analysis showed that these tailings did contain a toxic mixture of heavy metals and chemicals (Mud from Brazil dam disaster is toxic 2015). A year earlier, a tailings pond was breached at the Mount Polley copper and gold operation in Canada, contaminating waters downstream. In 2000, the Somes River in Romania was contaminated after the Baia Mare spill, where gold tailings were being treated with cyanide to extract additional value. In 1996, the Marcopper disaster in the Philippines inundated the Boac River with copper tailings. These disasters serve as examples of the continuing problems that can arise from tailings that mobilize into water systems (Plumlee et al. 2000).

Examining the effects of historic mines on current water quality helps communities develop effective regulations to prevent new mines from contaminating water. Mapping tailings locations and monitoring their water quality impacts require novel techniques that incorporate measures of historic mine waste as well as current mining operations. This paper shows that historic datasets can be used to inform current environmental decision-making. The so-called "soft data" found in the human processes that have historically transformed landscapes are often not fully explored or appreciated. Historical datasets, especially once spatialized, can help identify impacts from historic iron mining and provide environmental scientists and regulators with a better informed understanding of the challenges involved in landscape-scale remediation. This paper suggests a spatial and historical approach that land managers and policy makers can apply to assess the impacts of mining on affected watershed health.

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REFERENCES

Agency, Minnesota Pollution Control. 2008. *Appendix A: Impaired Waters and TMDL Fact Sheets and Maps*. St. Paul, MN: Minnesota Pollution Control Agency.

Anderson, P. 2016. *Guidance Manuel for Assessing the Quality of Minnesota Surface Waters for Determination of Impairment: 305(b) Report and 303(d) List*. 2016 Assessment and Listing Cycle.

Anderson, P., and I. Martin. 2015. *Standard Operating Procedures (SOP): Lake Water Quality Sampling*. St. Paul, MN: Minnesota Pollution Control Agency.

Anderson, P., W. Bouchard, D. Chrisopherson, and M. Feist. 2014. *Guidance Manual for Assessing the Quality of Minnesota's Surface Waters for Determination of Impairment: 305(b) Report and 303(d) List*. St. Paul, MN: Minnesota Pollution Control Agency.

Angelstam, P., K. Andersson, M. Isacson, D.V. Gavrilov, R. Axelsson, M. Bäckström, E. Degerman, M. Elbakidze, et al. 2013. Learning about the history of landscape use for the future: Consequences for ecological and social systems in Swedish Bergslagen. *Ambio* 42: 146–159. doi:10.1007/s13280-012-0369-z.

Axler, R., C. Larsen, C. Tikkanen, M. McDonald, S. Yokom, and P. Aas. 1996. Water quality issues associated with aquaculture: A case study in mine pit lakes. *Water Environment Research* 68: 995–1011.

Axler, Richard, S. Yokom, C. Tikkanen, M. McDonald, H. Runke, D. Wilcox, and B. Cady. 1998. Restoration of a Mine Pit lake from aquacultural nutrient enrichment. *Restoration Ecology* 6: 1–19.

Baeten, J., N. Langston, and D. Lafreniere. 2016. A geospatial approach to uncovering the hidden waste footprint of Lake Superior's Mesabi Iron Range. *The Extractive Industries and Society* 3: 1031–1045. doi:10.1016/j.exis.2016.09.003.

Bernhardt, E.S., B.D. Lutz, R.S. King, J.P. Fay, C.E. Carter, A.M. Helton, D. Campagna, and J. Amos. 2012. How many mountains can we mine? Assessing the regional degradation of central appalachian rivers by surface coal mining. *Environmental*

Science and Technology 46: 8115–8122. doi:10.1021/es301144q.
Bird, G. 2016. The influence of the scale of mining activity and mine site remediation on the contamination legacy of historical metal mining activity. *Environmental Science and Pollution Research* 23: 23456–23466.
Braungardt, C.B., E.P. Achterberg, F. Elbaz-Poulichet, and N.H. Morley. 2003. Metal geochemistry in a mine-polluted estuarine system in Spain. *Applied Geochemistry* 18: 1757–1771. doi:10.1016/S0883-2927(03)00079-9.
Byrne, P., P.J. Wood, and I. Reid. 2012. The impairment of river systems by metal mine contamination: A review including remediation options. *Critical Reviews in Environmental Science and Technology* 42: 2017–2077.
Cherry, D.S., R.J. Currie, D.J. Soucek, H.A. Latimer, and G.C. Trent. 2001. An integrative assessment of a watershed impacted by abandoned mined land discharges. *Environmental Pollution* 111: 377–388.
Church, S.E., P. von Guerrard, and S.E. Finger. 2007. *Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado*. U.S. Geological Survey Professional Paper 1651.
Clifford, J. 2017. *West Ham and the River Lea: A Social and Environmental History of London's Industrialized Marshland, 1839–1914*. Vancouver, BC: UBC Press.
Cummins, A., and I. Given. 1973. *SME Mining Engineering Handbook*, vol. 2. New York: Society of Mining Engineers.
Cunfer, G. 2008. Scaling the dust bowl. In *Placing History: How Maps, Spatial Data, and GIS are Changing Historical Scholarship*, ed. A.K. Knowles, 95–122. Redlands, CA: ESRI Press.
Davis, E.W. 1964. *Pioneering with Taconite*. St. Paul, MN: Minnesota Historical Society.
Forbes, J. 1953. Iron ore. In *Minerals yearbook metals and minerals. Bureau of mines*. Washington: Government Printing Office.
Grosbois, C., M. Meybeck, L. Lestel, I. Lefevre, and F. Moatar. 2012. Severe and contrasted polymetallic contamination patterns (1900–2009) in the Loire River sediments (France). *Science of the Total Environment* 435: 290–305.
Gutmann, M., D. Brown, A. Cunningham, J. Dykes, S. Hautaniemi Leonard, J. Little, J. Mikecz, P. Rhode, et al. 2016. Migration in the 1930s: Beyond the dust bowl. *Social Science History* 40: 707–740.
Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. *Managing California's Water: From Conflict to Reconciliation*. San Francisco, CA: Public Policy Institute of California.
Haunch, S., and A. MacDonald. 2011. The environmental legacy of historic mining activities in the Almond River catchment, Scotland. In *Mine Water—Managing the Challenges*. Aachen, Germany.
Haunch, S. 2013. Legacy of historic mining and water quality in a heavily mined Scottish river catchment. PhD thesis, Edinburgh: University of Edinburgh.
Hubbard, J. 1948. Spiral concentration. *Mining World* 13: 41–44.
Hudson-Edwards, K. 2016. Tackling mine wastes. *Science* 352: 288–290.
Hudson-Edwards, K., M. Macklin, and M. Taylor. 1997. Historic metal mining inputs to Tess river sediment. *The Science of the Total Environment* 194: 437–445.
Hunerlach, M.P., J.J. Rytuba, and C.N. Alpers. 1999. *Mercury contamination from hydraulic placer-gold mining in the Dutch Flat Mining District, California.* U.S. Geological Survey, Water-Resources Investigations Report 99-4018B, pp. 179–189.
Hunt, M. 1951. *Taconite: Iron ore bonanza*. Steelways, Iron and Steel Institute.
Impaired Lakes. 2012. *Minnesota Geospatial Commons (version Shapefile)*. St. Paul, MN: Minnesota Pollution Control Agency.
Iron Ore Concentrating Plants of Minnesota. 1920. *Skillings' Mining Review*, September 4.
Isenberg, A. 2005. *Mining California: An Ecological History*. New York: Hill and Wang.
James, L.A., and W.A. Marcus. 2006. The human role in changing fluvial systems: Retrospect, inventory and prospect. *Geomorphology* 79: 152–171.
Johnson, D.B., and K. Hallberg. 2005. Acid mine drainage remediation options: A review. *Science of the Total Environment* 338: 3–14.
Keeling, A., and J. Sandlos. 2015. *Mining and communities in Northern Canada: History, politics, and memory*. Calgary: University of Calgary Press.
Kohn, C., and R. Specht. 1958. The mining of taconite, lake superior iron mining district. *Geographical Review* 48: 528–539.
Lakes and water quality. 2017. Government. *Minnesota Pollution Control Agency*.
Langston, N. 2017. *Sustaining Lake Superior*. New Haven, CT: Yale University Press.
LeCain, T. 2009. *Mass Destruction: The Men and Giant Mines that Wired America and Scared the Planet*. New Brunswick: Rutgers University Press.
LeClerc, E., and Y. Wiersma. 2017. Assessing post-industrial land cover change at the Pine Point Mine, NWT, Canada using multi-temporal Landsat analysis and landscape metrics. *Environmental Monitoring and Assessment* 189: 19.
LiDAR Elevation, Arrowhead Region, NE Minnesota, 2011. *Shape and File GeoDataBase*. St. Paul, MN: Minnesota Department of Natural Resources. Davis, Kellogg & Severance Law Firm Records.
LiDAR Elevation, Central Lakes Region, Minnesota, 2012. *Shape and File GeoDataBase*. St. Paul, MN: Minnesota Department of Natural Resources.
Limerick, P.N., J.N. Ryan, T.R. Brown, and T.A. Comp. 2005. *Cleaning up abandoned hardrock mines in the west: Prospecting for a better future*. Report from the Center #7, Center of the American West, University of Colorado at Boulder, 47 pp.
MacFarlane, D. 2016. *Waukesha and great lakes water: some historical background*. NiCHE: Network in Canadian History & Environment. http://niche-canada.org/2016/06/22/waukesha-and-great-lakes-water-some-historical-background/.
MacKenzie, A.B., and I.D. Pulford. 2002. Investigation of contaminant metal dispersal from a disused mine site at Tyndrum, Scotland, using concentration gradients and stable Pb isotope ratios. *Applied Geochemistry* 17: 1093–1103.
Macklin, M.G., K.A. Hudson-Edwards, and E.J. Dawson. 1997. The significance of pollution from historic metal mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. *Science of the Total Environment* 194: 391–397.
Manuel, J.T. 2015. *Taconite Dreams: The Struggle to Sustain Mining on Minnesota's Iron Range, 1915–2000*. Minneapolis, MN: University of Minnesota Press.
McGarvey, D.J., and J.M. Johnston. 2013. "Fishing" for alternatives to mountaintop mining in Southern West Virginia. *Ambio* 42: 298–308. doi:10.1007/s13280-012-0346-6.
Miller, J. 1997. The role of fluvial geomorphic processes in the dispersal of heavy metals from mine sites. *Journal of Geochemical Exploration* 58: 101–118.
Mineland Reclamation: Minnesota's Program. 1988. *Division of Lands and Minerals*. Minnesota Department of Natural Resources.
Mineral Resources Data System. 2005. *Shape and File GeoDataBase*. Reston, VA: U.S. Geological Survey.

Minnesota's Impaired Waters List. 2017. Government. *Minnesota Pollution Control Agency*.
Moore, J.N., and H.W. Langer. 2012. Can a river heal itself? Natural attenuation of metal contamination in river sediment. *Environmental Science and Technology* 46: 2616–2623.
Moore, J.N., and S.N. Luoma. 1990. Hazardous wastes from large-scale metal extraction. *Environmental Science and Technology* 24: 1278–1285.
Mud from Brazil dam disaster is toxic, UN says, despite mine operator denials. 2015. *The Guardian*, November 25.
Muskie, E. 1972. *Clean Water Act. 40 C.F.R.*
Pellicori, D.A., C.H. Gammons, and S.R. Poulson. 2005. Geochemistry and stable isotope composition of the Berkeley pit lake and surrounding mine waters, Butte, Montana. *Applied Geochemistry* 20: 2116–2137. doi:10.1016/j.apgeochem.2005.07.010.
Plumlee, G.S., R.A. Morton, T.P. Boyle, J.H. Medlin, and J.A. Centeno. 2000. An Overview of Mining-Related Environmental and Human Health Issues, Marinduque Island, Philippines: Observations from a Joint US Geological Survey-Armed Forces Institute of Pathology Reconnaissance Field Evaluation, May 12–19, 2000. *US Geological Survey Open-File Report*.
Quivik, F. 1998. *Smoke and tailings: An environmental history of copper smelting technologies in Montana, 1880–1930*. Dissertation, University of Pennsylvania.
Ross, M.R., B.L. McGlynn, and E.S. Bernhardt. 2016. Deep impact: Effects of mountaintop mining on surface topography, bedrock structure, and downstream waters. *Environmental Science and Technology* 50: 2064–2074.
Savage, K., D. Bird, and R. Ashley. 2010. Legacy of the California gold rush: Environmental geochemistry of arsenic in the southern Mother Lode Gold District. *International Geology Review* 42: 385–415.
Seaber, P., P. Kapinos, and G. Knapp. 1994. *Hydrologic Unit Maps*. United States Geological Survey Water-Supply Paper 2294. U.S. Department of the Interior.
Singer, M.B., R. Aalto, L.A. James, N. Kilham, J. Higson, and S. Ghoshal. 2013. Enduring legacy of a toxic fan via episodic redistribution of California gold mining debris. *Proceedings of the National Academy of Sciences of the United States of America* 110: 18436–18441. doi:10.1073/pnas.1206191109.
Sullivan, M. 2014. *Tainted Earth: Smelters, Public Health, and the Environment*. New Brunswick: Rutgers University Press.
Surface Mining: Complete Reconciliation of the Abandoned Mine Land Fund Needed. 1988. *GAO/RCED-89-35*. Government Accountability Office.
Taggart, A. 1927. *Handbook of Ore Dressing*. New York: Wiley.
Technical Resource Document: Extraction and Beneficiation of Ores and Minerals. 1994. *EPA 530-R-94-030*. Washington, DC: U.S. Environmental Protection Agency: Office of Surface Waste.
The 8, 10, and 12 hydrologic unit boundaries for Minnesota. 2008. *Vector Digital Data*. Mounds View, MN: USGS.
The Lake Superior District. 1920. *The Iron Trade Review* 66.
Thomas, M.A., C.H. Conaway, D.J. Steding, M. Marvin-DiPasquale, K.E. Abu-Saba, and A.R. Flegal. 2002. Mercury contamination from historic mining in water and sediment, Guadalupe River and San Francisco Bay, California. *Geochemistry: Exploration, Environment, Analysis* 2: 211–217.
Van Allen, N., and D. Lafreniere. 2016. Rebuilding the landscape of the rural post office: A geo spatial analysis of the 19th century postal space and networks. *Rural Landscapes: Society, Environment, History* 3: 1–19.
Van Barneveld, C.E. 1913. *Iron Mining in Minnesota*. Minnesota School of Mines Experiment Station Bulletin 1. Minneapolis, MN: University of Minnesota.
Walker, S.R., H.E. Jamieson, A. Lanzirotti, G.E.M. Hall, and R.C. Peterson. 2015. The effect of ore roasting on arsenic oxidation state and solid phase speciation in gold mine tailings. *Geochemistry: Exploration, Environment, Analysis* 15: 273–291.
Water Quality: Describing Water Quality. 2017. Government. *Minnesota Department of Natural Resources*. http://www.dnr.state.mn.us/whaf/about/5-component/wq_concepts.html. Accessed 25 July 2017.
Water Quality Standards. 2017. Government. *Minnesota Pollution Control Agency*. https://www.pca.state.mn.us/water/water-quality-standards. Accessed 28 Feb 2017.
Wernstedt, K., and R. Hersh. 2010. Abandoned Hardrock Mines in the United States: Escape from a Regulatory Impasse. *William & Mary Environmental Law and Policy Review* 1: 25.
Worrall, R., D. Neil, D. Brereton, and D. Mulligan. 2009. Towards a sustainability criteria and indicators framework for legacy mine land. *Journal of Cleaner Production* 17: 1426–1434.
Watershed Boundary Dataset (WBD). *ESRI Shape and File GeoDataBase*. USGS and USDA-NRCS.
Yellishetty, M., P.G. Ranjith, and A. Tharumarajah. 2010. Iron ore and steel production trends and material flows in the world: Is this really sustainable? *Resources, Conservation and Recycling* 54: 1084–1094. doi:10.1016/j.resconrec.2010.03.003.
Young, G. 1932. *Elements of Mining*. New York: McGraw-Hill Book Company Inc.
Younger, P., and C. Wolkersdorfer. 2004. Mining impacts on fresh water environment: Technical and managerial guidelines for catchment scale management. *ERMITE Report: D6, The European Commission Fifth Framework Programme, Energy Environment and Sustainable Development*.
Zellie, C. 2005. *Mesabi Iron Range Historic Contexts, Itasca and St. Louis Counties, Minnesota Phase III Mitigation Study TH 169*. St. Paul, MN: Federal Highway Administration and Minnesota Department of Transportation.

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