Isotopic and Chemical Characterization of Water From Mine Pits and Wells on the Mesabi Iron Range, Northeastern Minnesota, as a Tool for Drinking Water Protection

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Abstract

The Biwabik Iron Formation is both a world-class source of iron ore and an important aquifer for the residents of the Mesabi Iron Range in northeastern Minnesota. Numerous public water supply wells draw from this aquifer, and several communities pump directly from abandoned mine pits for their water supply. It is important that the groundwater flow characteristics of this aquifer be determined so that drinking water supplies can be protected in a technically defensible manner.

The iron formation is early Proterozoic in age and consists primarily of fine-grained silica and iron minerals that were deposited as chemical sediments in a marine environment. The unit has little primary porosity. Groundwater flow through the aquifer is controlled predominantly by secondary features such as folds, high-angle faults, joints, and man-made mining structures.

Efforts at delineating source water protection areas on the Mesabi Range have been complicated by the extremely heterogeneous and anisotropic nature of porosity in the Biwabik Iron Formation aquifer. In the absence of reliable groundwater flow models for this type of setting, isotopic and chemical studies have been emphasized, in addition to hydrogeologic mapping.

Conservative environmental tracers such as chloride and the stable isotopes of oxygen and hydrogen have proved useful for 1) identifying wells that are receiving recharge from mine pits, 2) characterizing the tracer signature of those mine pits that may represent recharge areas for nearby public supply wells, and 3) quantifying the significance of these recharge areas for the purpose of targeting source water protection efforts.

Introduction

The Mesabi Iron Range of northeastern Minnesota (Figure 1) is one of the world’s most important sources of iron ore, having produced more than 3.6 billion metric tons of ore from more than 525 mines over the past 100 years (Morey, 1999). Mining along the Mesabi Iron Range began in the 1890's. Early mining activities focused on “natural ore”; portions of the Biwabik Iron Formation that had been enriched in iron content via solution weathering. Natural ore zones were localized along fracture and fault zones and were mined initially by underground and later surface mining techniques. Most natural ore zones were depleted by the late 1950's, after which time the focus of mining activities switched to the non-enriched iron formation or taconite. The onset of taconite mining in the 1960’s expanded existing natural ore pits into significantly larger and deeper excavations, some of which are still currently being mined. To date, taconite ore has accounted for approximately 30% of the iron ore mined on the Mesabi Range, although that percentage is bound to increase as taconite mining continues into the future (Morey, 1999).

The Mesabi Iron Range is home to approximately 37 public water suppliers, 22 of which fall into the community classification (municipalities or mobile home parks). The remaining 15 public water systems include several mining companies, along with some relatively small systems such as motels and restaurants. Most of these public water suppliers rely on groundwater, which supplies 29 of the 37 systems. The remaining systems rely on surface water in the form of water-filled mine pits. Of the public water suppliers that rely on groundwater, 11 use at least one well that is completed in the Biwabik Iron Formation. The remaining wells are typically completed in glacial sand and gravel deposits that exist locally above the bedrock. In summary, 15 communities and several mining companies on the Mesabi Iron Range rely on water derived from the Biwabik Iron Formation as a drinking water source. The total population served by these public water systems is in excess of 55,000.
Figure 1. Location of the Mesabi Iron Range.

Large water suppliers in Minnesota are required to delineate scientifically calculated wellhead protection areas (WHPAs) for the purpose of drinking water protection. Traditional WHPA delineation approaches based on models that simulate the flow of groundwater flow through porous media are not applicable to the Biwabik Iron Formation aquifer because it is dominated by fracture or conduit flow. As a result, the Minnesota Department of Health (MDH) has focused on alternative methods of determining the capture zones for these wells. These methods rely heavily on 1) characterization of the chemical and isotopic signature of mine pits located along the recharge area for the Biwabik Iron Formation aquifer, and 2) correlation between the chemical and isotopic signatures of mine pits and public water supply wells.

Geologic Setting of the Mesabi Iron Range

The Biwabik Iron Formation is part of a Paleoproterozoic series of metasediments termed the Animikie Group, that outcrop or subcrop along the 120 mile strike length of the Mesabi Iron Range (Morey, 1999). The Animikie Group lies unconformably on predominantly granitic rocks of Archean age collectively termed the Giants Range Granite. These granitic rocks form the topographic high-ground at the northern margin of the Mesabi Iron Range known as the Giants Range, which for much of its length constitutes the Laurentian watershed divide that separates surface water that flows north towards Hudson Bay from that which flows south towards either Lake Superior or the Mississippi River. The Animikie Group is comprised of three formations. The basal Animikie unit is the Pokegama Formation, which is an orthoquartzite with appreciable argillite and siltstone (Ojankagas et. al., 2004). This unit ranges in thickness from less than 25 ft at the eastern end of the
Mesabi Iron Range to as much as 360 ft at its western end (White, 1954). The Pokegama Formation is conformably overlain by the Biwabik Iron Formation, which is composed primarily of chert and iron minerals that were deposited as marine chemical sediments. The Biwabik Iron Formation ranges in thickness from less than 200 ft at its eastern end to as much as 750 ft towards the central portion (Morey, 1999). The formation has been subdivided into four members throughout most of the Mesabi Range based primarily on textural differences. These are, from top to bottom, 1) Upper Slaty; 2) Upper Cherty; 3) Lower Slaty; and 4) Lower Cherty (White, 1954). The slaty members are more fine-grained and thinly laminated than the cherty members, which tend to be massive and granular. Differences in mineralogy are also noted, whereby the slaty members are composed primarily of iron silicates and iron carbonates whereas the cherty members are primarily made up of chert and iron oxides (Morey, 1999). A notable marker horizon, termed the Intermediate Slate, is present at the base of the Lower Slaty for much of the Mesabi Iron Range. The Intermediate Slate is a thin-bedded, black, organic-rich slate that reportedly contains volcanic ash (Morey, 1993). The Biwabik Iron Formation is conformably overlain by a thick greywacke-shale sequence termed the Virginia Formation (Morey, 1983).

The general structure of the Animikie Group on the Mesabi Iron Range is that of a gently dipping homocline that strikes east-northeast and dips 5-15° SE. This simple geometry is disrupted locally by folding and faulting, some of which appears to have resulted from reactivation of high-angle faults in the Archean basement (Morey, 1999). Morey (1999) estimates that about 80 % of the natural orebodies on the Mesabi Iron Range are spatially related to faults. These tend to be steeply dipping, form zones ranging from 20 to 50 ft wide, and have apparent displacements ranging from 40 to 200 ft (Morey, 1999). Faults may be filled by veins of quartz, with lesser stilpnomelane, kaolinite, and iron or manganese oxides. Some quartz veins within the orebodies are parallel to the bedding plane (Morey, 1999). The natural orebodies themselves show considerable evidence of deformation, most commonly slumping related to the removal of 40-60 % of the original iron formation by leaching of silica (Morey, 1999).

The Animikie Group is locally overlain by mostly clastic marine strata of Cretaceous age termed the Coleraine Formation. Where present, the Coleraine Formation may attain a maximum thickness of approximately 100 ft (Morey, 1999). This unit locally contains iron-rich conglomerate that includes clasts of oxidized Biwabik Iron Formation, thereby setting a minimum age for the formation of the natural ore.

Glacial drift of late Wisconsinan-age covers much of the Mesabi Iron Range and ranges in thickness from a few feet at the northern margin of the study area along the Giants Range, to a maximum of approximately 200 ft along its southern margin. Three major morainal till units and associated glaciofluvial outwash deposits cover most of the area (Winter, 1973). The stratigraphically lowest till unit, termed the basal till, is a dark-greenish and brownish-gray till that is sandy, silty, clayey, and calcareous. The middle bouldery till ranges widely in color from gray to yellow, and consists of sands and silts, with abundant cobbles and boulders. The surficial till is brown in color; sandy, silty, and calcareous; and is generally less than 30 ft thick in the area. Glaciofluvial outwash deposits lie stratigraphically between the surficial and bouldery tills, and often lie between the bouldery and basal till or bedrock (Winter, 1973). These outwash deposits consist largely of sands, gravels, and boulders. The outwash aquifers are of limited extent and, although they are important locally as sources of public water supply, they provide a relatively small proportion of the total amount of water used by communities along the Mesabi Iron Range.

**Groundwater Movement**

The Biwabik Iron Formation is the uppermost bedrock unit throughout most of the study area and is the dominant bedrock aquifer along the Mesabi Iron Range because of the combination of fracturing and solution-weathering that have occurred locally. These same factors were responsible for the development of the natural ores that have accounted for the bulk of the iron ore production on the range. The underlying Pokegama Formation and overlying Virginia Formation generally have not been fractured or weathered to the extent of the Biwabik Iron Formation and are generally considered confining units for the iron formation, at least on a regional scale.
The Biwabik Iron Formation has little primary porosity, and groundwater flow through this unit is likely controlled by faults, joints (both high-angle and bedding-plane), zones of solution-weathering, and man-made mining structures such as drifts and shafts. The distribution of hydraulic head in the aquifer is poorly known because of the lack of wells with water level data in this area and the dynamic nature of mining and pit dewatering. It is likely that under pre-mining groundwater conditions: 1) the water table existed almost entirely in the glacial deposits, 2) the Biwabik Iron Formation was generally confined by overlying glacial till in addition to the overlying Virginia Formation, and 3) the direction of groundwater flow in both the glacial deposits and the Biwabik Iron Formation was generally to the south or southeast. Currently, mining activities have dewatered much of the glacial drift and Biwabik Iron Formation adjacent to active taconite pits. Mining has created windows in the till confining layer, placing the water table locally in the Biwabik Iron Formation. Recharge areas for the Biwabik Iron Formation thus include those mine pits that are not being dewatered, underground workings that are connected to the surface via shafts, adits or collapse features, and those areas between the mine pits and the northern limits of the Biwabik Iron Formation where the glacial sediment cover is thinnest. Discharge from the Biwabik Iron Formation is locally dominated by mine pit dewatering and pumping from public water supply wells. Recharge and discharge zones are, therefore, closely spaced though widely different in water level elevation, resulting in steep vertical gradients and relatively deep penetration of recent recharge, as indicated by tritium data that show post-1953 recharge has penetrated nearly the entire stratigraphic thickness of the Biwabik Iron Formation within its subcrop area.

**Mine Pit Influence**

As noted above, mine pits can function as recharge or discharge areas for the Biwabik Iron Formation depending on their mining status and stage of filling. Dewatered taconite pits function as sinks, capturing
groundwater primarily from the Biwabik Iron Formation and possibly glacial outwash, in addition to surface water runoff and precipitation (Adams, 1994). The only losses that occur are a result of evaporation. This relationship can be expressed as:

$$\Delta S = GW + SW + P - ET - Q$$

where $$\Delta S$$ is the change in storage, GW is groundwater inflow, SW is surface water inflow, P is precipitation, ET is evapotranspiration and Q is discharge. Because plant growth (and thus transpiration) is limited in and around the mine pits, this equation can be simplified by expressing the difference between precipitation and evapotranspiration as net precipitation (Net P). Therefore, pit empty conditions can be expressed as:

$$\Delta S = GW + SW + Net\ P - Q$$

As pumping ceases this is further simplified to:

$$\Delta S = GW + SW + Net\ P$$

Mine pit filling is initially rapid due to the steep hydraulic gradients present in the aquifer(s) adjacent to the pits and the relatively high value of net precipitation that reflects small evaporative losses related to the initially small exposed water surface area. Pit filling rates decrease with time as rising pit water levels result in decreasing hydraulic gradients and net precipitation decreases as a result of increasing evaporative losses. Groundwater outflow begins to occur once the water level in the pit exceeds that of an adjacent aquifer (Adams, 1994). At that point, the mine pit may function as a source of recharge for a water supply well that is open to that aquifer. Continued filling of the pit may result in surface water outflow. Eventually a mine pit will reach equilibrium, as expressed by:

$$SW\ Out + GW\ Out = GW\ In + SW\ In + Net\ P\ In$$

Note that often times surface water inputs are relatively negligible at many mine pits due to their proximity to the Laurentian Divide and because, if streams were present during active mining, they were commonly rerouted by the mining companies.

The relationship between public water supply wells and mine pits on the Mesabi Iron Range is important to address because 1) most are located in relatively close proximity with one another, often within 0.5 mile, 2) fluctuating water levels in mine pits can impact the performance of adjacent wells, 3) the water quality of mine pits can be intimately linked to that of nearby wells, and 4) long-range mining plans suggest the potential for significant expansion of some existing operations, thereby potentially increasing the areal extent and depth of these features.

**Environmental Tracers and Mine Pits**

As mine pits empty and then fill, the water contained therein takes on a unique chemical and isotopic signature that is based on the relative importance of each of the source and loss terms in their water budget for their stage of filling. In general, when mine pits are near empty the inflowing water is dominated by groundwater and evaporative losses are relatively small due to the short residence time and small surface area of the pit water pond. In this case, the isotopic signature of the water will most likely approximate that of meteoric water, assuming that the inflowing groundwater was not recharged from a fractionated source. As the pits fill, groundwater inflow decreases and evaporation increases. As a result, the water in the pits begins to migrate off of the meteoric water line along an evaporation trend (Figure 3). This process reverses when the pits are dewatered. Water samples that represent a mixture of mine pit water and directly infiltrated groundwater will plot along this tie-line, and the percentage of mine pit water present in the mixture can be determined via mass-balance analysis. This type of approach has commonly been applied to problems of groundwater-surface water interaction at natural lakes and rivers (Krabbenhof et. al, 1990, Dysart, 1988).
The chemical makeup of the pit water reflects a similar cycle. When nearly dewatered, the pit water chemistry reflects that of the dominant aquifers (or preferred flow horizons within those aquifers) penetrated by the pit plus contributions from precipitation. As a pit fills, groundwater inputs are slowly reduced in response to decreasing hydraulic gradients, and the relative contribution of precipitation may increase. These changes, along with those related to oxidation, mixing, and mineral precipitation and dissolution reactions resulting from interaction with geological materials in the pit, will affect the mine pit water chemistry through time.

Among the most useful chemical constituents for characterizing mine pits on the Mesabi Iron Range are chloride and sulfate. Chloride is chemically conservative and present in low natural concentrations. Values greater than approximately 2 mg/l are indicative of human influence, most likely from the use of road de-icing salts within the catchment area of a mine pit. Sulfate can be a good indicator of recharge provenance because sulfur-bearing mineral phases are relatively scarce in the Biwabik Iron Formation and adjacent rocks, with the exception of the Coleraine Formation, the Intermediate Slate and the Virginia Formation, each of which are known to contain pyrite, at least locally (Morey, 1973, Ojakangas, et.al., 2004). However, sulfate is subject to chemical reduction and its concentration may be limited by gypsum formation in calcium-rich water. As a result, sulfate tends to be a less reliable chemical tracer.

By characterizing the chemical and isotopic composition of water from mine pits and comparing these results with water samples from nearby wells, it is possible to identify those mine pits that are functioning as sources of recharge. This information can be applied to the delineation of the wellhead protection area for a public supply well, which is especially important in this setting where capture zone flow modeling is of suspect value. The delineation of wellhead protection areas in Minnesota is commonly accomplished using either analytic element or numerical groundwater flow models. While such models provide reasonable solutions for porous media aquifers, their application in fractured or solution-weathered aquifers is more tenuous. For such models to
accurately simulate groundwater movement through a fractured media, they commonly require a large amount of high-quality data on fractures related to their distribution, apertures, hydraulic conductivity and connectivity. In the absence of such data, a different approach to capture zone analysis is required.

**Keewatin Example**

*Hydrogeologic Setting*

The city of Keewatin is located on the western Mesabi Iron Range and utilizes two water supply wells that are completed in the Biwabik Iron Formation. Well No. 1 is 8 inches in diameter and open from 240 to 600 feet. This well is apparently open from the Upper Cherty to the Lower Cherty member (Figures 4 and 5). Well No. 2 is 10 inches in diameter and open from 373 to 473 feet. This well is apparently open to only the Lower Cherty member.

Well No. 1 is located in the center of town whereas Well No. 2 is immediately adjacent to the Carlz Pit, which is an old natural ore mine that is now mostly water-filled (Figure 4). Each of the mine pits in the Keewatin area began as natural ore mines. The Stevenson, Section 18, Russell and Bennett Pits have subsequently been expanded into taconite operations and are currently being dewatered and mined by Keewatin Taconite. Dewatering at these pits commenced in the late 1960's. The Carlz, St. Paul, Perry, Gordon, Sargent and Mesabi Chief Pits have not been mined since natural ore operations ceased prior to the mid 1960's. The Mesabi Chief Pit is scheduled for future taconite mining; dewatering efforts at this pit were initiated in October, 1995.

The Biwabik Iron Formation, where exposed in the Keewatin area, is heavily fractured. Many high-angle joints roughly parallel the orientation of the natural ore pits, although joint interpretation is complicated by the effects of blasting along the pit walls. In addition to the dominant jointing orientation, conjugate joint sets also exist and bedding plane joints are common. Mapped faults are indicated in Figure 4; most trend approximately west by northwest. A similar structural grain is also indicated by the trend of aeromagnetic data (Chandler, 1985).

Records on file at the city of Keewatin and Keewatin Taconite reflect the dynamic nature of the local hydrogeology. For example, 1) water levels in the Keewatin wells rose approximately 200 feet over the period that followed the cessation of mining in the Carlz Pit in the early 1960's and preceding dewatering at the Mesabi Chief Pit in 1995; and 2) prior to the expansion of Keewatin Taconite in the mid 1970's, water levels in the Stevenson and Bennett Pits were approximately 150 feet higher than currently measured, indicating that the Stevenson Pit area may have been the high point in the local potentiometric surface at that time.

Figure 6 shows water level elevations for Keewatin’s wells and selected mine pits for the period 1995 through 2002. Note that Keewatin Well No. 1 has not been accessible for water level measurement since 1998. This graph clearly shows the effect that dewatering the Mesabi Chief Pit has had on water levels in nearby pits and wells. Exceptions include the Perry Pit, which has had a very subdued response despite its proximity to the Mesabi Chief Pit and the Carlz Pit, which has apparently had no response. The reason these pits have shown little response may be due to a poor or indirect hydraulic connection owing to 1) sedimentation or 2) failure to penetrate the hydraulically conductive portions of the aquifer. The dramatic response seen initially at the city wells and at the Sargent and St. Paul Pits suggests a strong hydraulic connection between them and the Mesabi Chief. Anecdotal evidence suggests that these mine pits may be physically connected via underground mining structures.

*Chemical and Isotopic Results*

Initially, general water chemistry and tritium samples were collected from only the city wells in 1991 as part of a study on the usefulness of tritium as an indicator of well vulnerability (MDH, 1991). Subsequently, two rounds of samples were collected at all accessible mine pits and wells in the area in February and August of 1996. These samples were analyzed for general water chemistry in addition to oxygen-18, deuterium and tritium. Field measurements were also taken for temperature, conductivity, pH, dissolved oxygen and redox potential. Most pit water samples were taken from discharge piping off turbine pumps. In a few instances, samples were taken by dipping bottles into standing water. During this period, the St. Paul Pit was accessible for sampling only in August, because the route down to the sampling point was treacherous in February. The
Figure 4. Bedrock geology of the Keewatin area (after Lively, et. al, 2002).

Figure 5. Geologic cross-section through Keewatin.
Keewatin city wells were sampled again for general water chemistry in addition to oxygen-18 and deuterium in 1998 as part of a Minnesota Department of Natural Resources study on water quality on the Mesabi Iron Range (Berndt and others, 1998). Most recently, the city wells and the Carlz and Mesabi Chief Pits were sampled for oxygen-18, deuterium and chloride in 2001. In each instance, isotopic analyses were conducted at the Environmental Isotope Laboratory at the University of Waterloo. Water chemistry analyses have been conducted at the MDH Lab, except for the 1998 study that utilized the chemical lab at the Department of Geology and Geophysics at the University of Minnesota. Well water samples were taken from raw water taps and collected only after three successive stable readings were recorded for temperature, conductivity and pH.

Analysis of major ion concentrations show that the results of the 1996 sampling event fall into three groups:

1) Well No. 1 produced water that is of a Ca-Mg-HCO$_3$ type with very little sulfate or chloride.

2) The Carlz Pit and Well No. 2 produced Ca-Mg-SO$_4$ water with major but subordinate bicarbonate and minor chloride. The relatively high sulfate values associated with this group may be due to pyrite oxidation. Casual observation of waste rock from the Carlz Pit revealed the presence of pyrite along fractures in numerous samples.

3) The remaining samples were of either a Ca-Mg-HCO$_3$ or Mg-Ca-HCO$_3$ composition, with sulfate values intermediate between groups 1 and 2. Chloride values of this group were comparable with group 2.

All tritium results, with the exception of Well No. 1, were in the range of 12.7 to 27.1 tritium units (TU). This indicates that post-1953 water dominates the flow systems in the Biwabik Iron Formation over its subcrop area. Although definitive groundwater ages cannot be determined from these results, they are consistent with the range noted for precipitation in the late 1950's and since the early 1970's from data collected at Ottawa, Canada. It seems most likely that these results reflect recharge that has occurred over the last 25 years. It is unlikely that late 1950's recharge would have persisted in this setting because of the intensive dewatering that has occurred in
the aquifer since that time. Well No. 1 produced water containing 1.5 to 2.8 tritium units, suggesting only a minor component of post-1953 recharge. This may be due to the presence of the Virginia Formation, a likely confining unit overlying the Biwabik Iron Formation at this location, and the relatively long distance between this well and the mine pits.

Oxygen-18 and deuterium proved among the most useful tools for determining characteristic source water signatures. When the 1996 oxygen-18 and deuterium results for all samples are plotted, three groupings result:

1) Water from Keewatin Well No. 1 and the Stevenson Pit plotted consistently within the range of analytical uncertainty of the meteoric water line (Figure 7). Therefore, these samples were characterized by unfractionated recharge.

2) Water from the natural ore pits plotted well off the meteoric water line, indicating significant fractionation.

3) The remaining samples plotted along a regression line between groupings 1 and 2. Water from these sources has undergone some degree of fractionation.

**Figure 7. Stable isotope results from Keewatin for February, 1996.**

**Trend Analysis**

Figure 8 shows the results from 1996 and 2001 for the city wells and the Carlz and Mesabi Chief mine pits. These clearly show the effect of dewatering at the Mesabi Chief on the isotopic signatures at these sites. By
September of 2001, 1) water from Well No. 1 plotted off of the meteoric water line, 2) Well No. 2 plotted even farther off than the 1996 value, similar to the Carz Pit water, and 3) water from the Mesabi Chief Pit had migrated towards the meteoric water line. Figure 9 displays this information in terms of a mass-balance mixing analysis. In 1996, approximately 50% of the water at Well No. 2 could have originated at either the Carz or Mesabi Chief Pits, whereas no appreciable pit water recharge was evident at Well No. 1. By 2001, water from the nearly dewatered Mesabi Chief Pit was trending towards the meteoric water line, whereas water from the Carz Pit was increasingly fractionated. Assuming that the Carz Pit was functioning as a recharge boundary, nearly 70% of the water from Well No. 2 and 10-15% of the water at Well No. 1 could have originated from that pit.

Figure 8. Stable isotope results from 1996 (left) and 2001 (right).

When chloride data are added to this review, these trends are accentuated (Figure 10). Both Keewatin wells and the Carz Pit have trended towards enrichment in oxygen-18 and chloride over the time period represented by these samples, which is five years for the mine pits and 10 years for the wells. This effect has been relatively dramatic at Well

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No. 2 and the Carlz Pit, which have shown roughly the same magnitude of change in these parameters. While Well No. 1 has shown roughly the same trend, the magnitude of change has been much smaller. Water from this well is still relatively distinct in terms of being isotopically light and low in chloride compared with other samples from the Keewatin area. Water from the Mesabi Chief Pit has trended in the opposite direction, towards depletion of oxygen-18 and a slight decrease in chloride. This likely reflects the dewatering that has occurred at this pit. When the pit was originally sampled in 1996, dewatering had only recently begun, the pit was essentially water-filled, and the residence time of that water within the pit must have been relatively long in order for the isotopes to be enriched as they were. By the time the pit was sampled in 2001, the pit was mostly dewatered, the residence time of that water was relatively short and the water balance had probably shifted towards increasing inflows of groundwater compared with surface water or precipitation.

Figure 10. Chloride and oxygen-18 data through time for Keewatin.

Taken together, the water level and chemical data suggest that the Mesabi Chief and its adjoining hydraulically connected pits (Sargent and St. Paul) may serve as a source of water to the Keewatin city wells in the absence of dewatering. But with dewatering occurring, the Mesabi Chief Pit area becomes a groundwater sink and groundwater flow to the city wells is re-routed. Presumably, the bulk of this flow must come from the area of the Carlz Pit. The Carlz is the only nearby mine pit that is not being dewatered directly or indirectly. The similarity between the chemical and isotopic signatures at the Carlz Pit and Well No. 2, in addition to the similar trend data for both city wells with respect to the Carlz, implies that this is a plausible scenario.
If the Carlz Pit is a transient source of water for the city wells, then it must be explained why the difference in water levels between these features is so great. For example, over 100 feet of water level difference was measured in late 2002 between the Carlz Pit and Well No. 2. One explanation is that the leakage from this pit occurs slowly, possibly as a result of sedimentation or due its stratigraphic position within the Biwabik Iron Formation. Best estimates place the base of this mine pit above the Intermediate Slate horizon (Figure 5). The construction records for both city wells seem to suggest that the bulk of their water is derived from below this horizon. It is possible that portions of the Lower Slaty member of the Biwabik Iron Formation may be functioning as a semi-confining unit between the Upper and Lower Cherty members. If this is the case, then a stronger hydraulic connection between the city wells and the Mesabi Chief Pit would make sense, because the Mesabi Chief partially penetrates the Lower Cherty member. The lack of a strong evaporative signature at Well No. 1 during the early stages of dewatering at the Mesabi Chief likely reflects the relatively low gradient that likely exists under static conditions.

**Keewatin Wellhead Protection Area (WHPA) Delineation Approach**

The WHPA for the Keewatin wells was delineated by 1) calculating a radius around each well to represent an inner protection zone, 2) using the existing water level and water chemistry data to infer which mine pits may function as potential sources of recharge for the wells, and 3) including the surface watersheds for those mine pits in the protection areas.

The radii were calculated using the following equation:

$$r = \frac{Q}{nL\pi}$$

where \(r\) is the radius around the well, \(Q\) is the volume of water pumped by the well over a given time period (in this case 10 years), \(n\) is the effective porosity, and \(L\) is the combined thickness of the water-producing horizons in the aquifer.

According to the chemical and isotopic data presented above, the WHPA likely changes as a function of mine pit dewatering. Figure 11 shows the WHPA for the current scenario in which the Mesabi Chief Pit is dewatered. In this scenario, the Carlz is the only mine pit that, along with its surface watershed, is included in the WHPA. Figure 12 shows a possible future configuration of the city’s WHPA after the Mesabi Chief Pit has once again filled with water. In this scenario, both the Carlz and the Mesabi Chief Pits are included, along with their surface watersheds. The area between the calculated radius for Well No. 1 and the surface watershed for the Mesabi Chief Pit is included based on extending the radius along a trend that reflects the dominant controls on flow in the Biwabik Iron Formation, which are the hydraulic gradient, the stratigraphic dip and the dominant grain of faulting and fracturing.

**Conclusions**

Isotopic and chemical data provide a useful means for estimating the relative importance of mine pits along the Mesabi Iron Range as recharge boundaries for public water supply wells. This information should be used in prioritizing wells for wellhead protection planning and for the delineation of wellhead protection areas. In addition, these data provide important clues to the hydrogeologic characteristics of the Biwabik Iron Formation and may allow for identification of preferred flow horizons within the unit. Development of a hydrostratigraphic model of the Biwabik Iron Formation should result in increasingly accurate wellhead protection area delineations.
Figure 11. WHPA for Keewatin wells with Mesabi Chief Pit dewatered.

Figure 12. Proposed WHPA for Keewatin with Mesabi Chief Pit water-filled.
References:


Biographical Sketch

Mr. Walsh has been with the Minnesota Department of Health (MDH) since 1989. His current responsibilities include assessing the vulnerability of the state's public water supply wells, working with public water suppliers on the development of wellhead protection plans and conducting special studies relating to drinking water protection.

Prior to coming to the MDH he was involved in mineral exploration and mining in western South Dakota for 5 years.

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