STRATUS CONSULTING

# Comments of the Keweenaw Bay Indian Community in Opposition to the Issuance of an Underground Injection Control Permit to Kennecott Eagle Minerals Company (Application No. MI-103-5W20-0002)

*Prepared for:*
Keweenaw Bay Indian Community
16429 Bear Town Road
Baraga, MI 49908

# Comments of the Keweenaw Bay Indian Community in Opposition to the Issuance of an Underground Injection Control Permit to Kennecott Eagle Minerals Company (Application No. MI-103-5W20-0002)

*Prepared for:*

Keweenaw Bay Indian Community
16429 Bear Town Road
Baraga, MI 49908

*Prepared by:*

Ann S. Maest
Stratus Consulting Inc.
PO Box 4059
Boulder, CO 80306-4059
303-381-8000

and

Robert Prucha
Integrated Hydro Systems

January 15, 2009
SC11598

# Contents

**Appendices**

C Intervenor's exhibit 214 (referenced in Chapter 2) from Petitions Of The Keweenaw Bay Indian Community, et al. On Permits Issued To Kennecott Eagle Minerals Company (Michigan Department of Environmental Quality).

D Testimony of Glenn Miller (referenced in Chapter 3). Excerpt from Hearing Transcript, Vol. 11, Petitions of the Keweenaw Bay Indian Community, et al. on Permits Issued to Kennecott Eagle Minerals Company (Michigan Department of Environmental Quality, May 12, 2008). (electronic only)

# Figures

# Tables

# List of Acronyms and Abbreviations

| | |
|---|---|
| ABA | acid-base accounting |
| bgs | below ground surface |
| CRP | concentrate reduction process |
| EC | electrical conductivity |
| ft | feet |
| GDPA | Groundwater Discharge Permit Application |
| GIS | geographical information system |
| gpm | gallons per minute |
| GSI | groundwater-surface water interface |
| in | inch |
| KBIC | Keweenaw Bay Indian Community |
| KEMC | Kennecott Eagle Mineral Company |
| $km^2$ | square kilometers |
| LHA | lifetime health advisory |
| m | meter |
| MCLG | maximum contaminant level goal |
| MDEQ | Michigan Department of Environmental Quality |
| mg/L | milligrams per liter |
| MPA | Mine Permit Application |
| MSU | massive sulfide unit |
| NCWIB | Non-Contact Water Infiltration Basins |
| NWF | National Wildlife Federation |
| RO | reverse osmosis |

| | |
|---|---|
| SC | specific conductance |
| SMCL | secondary maximum contaminant level |
| SMSU | semi-massive sulfide unit |
| | |
| TDRSA | temporary development rock storage area |
| TDS | total dissolved solids |
| TVD | total vertical depth |
| TWIS | treated water infiltrations system |
| | |
| μmhos/cm | micro-mhos per centimeter |
| μS/cm | microSiemens per centimeter |
| UIC | Underground Injection Control |
| USCS | Unified Soil Classification System |
| USDW | underground sources of drinking water |
| USGS | U.S. Geological Survey |
| | |
| WWTP | wastewater treatment plant |

# Executive Summary

The aquifers that will be impacted by Kennecott Eagle Mineral Company's (KEMC's) discharges are protected underground sources of drinking water (USDWs) because they contain a sufficient quantity of groundwater to supply a public water system; contain fewer than 10,000 milligrams per liter (mg/L) total dissolved solids; and have not been declared exempted aquifers under the Underground Injection Control (UIC) program. Assessing realistic potential impacts to the drinking water aquifer potentially impacted by KEMC's treated water infiltration system (TWIS) requires a thorough understanding of several interrelated hydrogeologic and geochemical issues, including the current and post-discharge groundwater flow systems; water quality and quantity entering and exiting the treatment plant; and the behavior of the TWIS discharge in the aquifer.

Our analysis shows that KEMC has seriously underestimated the potential impacts to the USDWs in the TWIS area. KEMC's analysis of the potential impacts to the USDWs was inadequate or flawed in how it considered inflows to the TWIS, wastewater treatment plant (WWTP) issues, and hydrogeologic and geochemical issues downgradient of the TWIS. A summary of the major issues related to these areas is included herein.

## S.1 Inflows to the TWIS

The major hydrogeologic issue regarding inflow to the TWIS is that KEMC's estimates of mine inflow are too low by several factors to an order of magnitude. This is a critical factor in the overall design of the TWIS, because the largest component of flow into the TWIS is inflow to the proposed underground mine. KEMC's modeled estimates of mine inflow are too low for the following reasons:

- Hydrogeologic characterization and conceptualization were inadequate
- Modeling did not include or consider major water-conducting structural features present throughout the area
- Modeling assumed that faults in the lower bedrock did not continue into the upper bedrock
- Effects of the crown-pillar failure in the mine or the increase of hydraulic conductivity due to dilation of the rock mass were not evaluated as a contingency or as part of the model

- Effects of mine workings, including the access tunnel, were not considered in the model

- Simulated flows were actually not high enough to dewater the access tunnel and the lower portions of the mine.

When more realistic assumptions are used as modifications to the Golder FEFLOW model, much higher inflow estimates are predicted. The more realistic higher inflows are supported by actual inflow rates for other, similar underground mines in the area, which KEMC did not consider.

In addition to underestimating likely mine and WWTP inflow rates, KEMC has underestimated the concentrations of contaminants in mine drainage water, and has, therefore, underestimated contaminant concentrations in water entering the WWTP. The following points describe the relevant geochemical issues and briefly explain why we believe KEMC's analysis underestimates input concentrations to the WWTP:

- The Eagle deposit (a massive sulfide ultramafic ore body) is similar to other ore bodies that have produced acidic waters with high concentrations of base metals such as nickel and copper.

- The ore and its host rock, which comprise the vast majority of the managed material at the Eagle Project, clearly have a moderate to high ability to produce acid and contaminants and a low ability to neutralize the acid produced. The surrounding sedimentary rocks also have a high ability to produce acid and leach metals, with somewhat more ability to neutralize the acid produced.

- KEMC's assessment of mine leachate quality is not representative of conditions expected in the underground mine during or after operations. KEMC ignored the presence of the development rock in the underground mine and the presence of a larger and more mineralized crown pillar, and underestimated the surface area and mine drainage concentrations, including concentrations of nitrate in the underground mine during operations.

- The comparison of our and KEMC's modeled WWTP inputs shows that predicted concentrations of many metals, including aluminum, barium, beryllium, cadmium, calcium, cobalt, copper, iron, lead, magnesium, manganese, mercury, nickel, and zinc are substantially higher in our more realistic analysis. The higher values are largely the result of the higher predicted concentrations in drainage coming into the underground mine. Therefore, KEMC's predictions of water quality entering the WWTP are very likely underestimated.

## S.2 Water Treatment Issues

Wastewater from sulfide mining, and the Eagle Project in particular, poses significant treatment challenges. The composite water from the mine (which derives from many sources) is unusual and possibly unique because it includes acid mine drainage, saline water, and the presence of boron, which is notoriously difficult to remove. Individually, these types of wastewaters are treated relatively successfully, but the treatment of a combination of such wastewaters is untested and remarkably complicated. The fact that the WWTP contains so many components is an indication of how difficult it will be for KEMC to treat the wastewater generated by the mine to acceptable levels. The salient treatment issues are summarized below:

- The most common type of treatment for acid mine drainage is lime precipitation, and the most common type of treatment for saline waters is reverse osmosis (RO). Because of the unique combination of contaminants, both types of treatment are proposed for the Eagle Project WWTP. While other RO systems have worked for mine drainage, this system is one of the only ones that will be required to work 24 hours a day, seven days a week. Given its complexity, uniqueness, and lack of proven success, it is highly unlikely that the system will be that reliable.

- We expect that the influent volume for the WWTP easily will be one order of magnitude higher than predicted by KEMC. If the water volume is higher than KEMC predicts for the WWTP [350 gallons per minute (gpm)], the system will fail because its design capacity will be exceeded. The only solution would be to increase the size of the treatment system or to discharge untreated or only partially treated wastewater. Increasing the size of the WWTP will require a major redesign effort and a major increase in the capacity of the TWIS and contact water storage basin facilities on the Site.

- The WWTP influent water quality likely will be substantially more contaminated than predicted, which will have an impact on the first stages of the water treatment system (first RO system), as well as the concentrate reduction process (CRP). When we apply the same removal efficiencies to our more realistic higher influent concentrations, we find that a number of contaminants will exceed the Michigan Department of Environmental Quality (MDEQ) permit limits and Michigan standards for drinking water, and the TWIS discharge would not be protective of the USDW.

- KEMC does not have a contingency plan for treatment of higher than expected volumes of water or water with substantially poorer quality. The main storage contingency for higher WWTP inflows is diversion to the development rock storage area. If water needs to be diverted to the waste rock facility, the water will need to be retreated. The acid generated in this system will require additional treatment to allow for passage through the RO system. The additional lime precipitation required will generate additional sludge, and the disposal of sludge has not been adequately addressed by KEMC. In addition, KEMC does not have a clear plan for quality assurance of the treatment process.

## S.3 Downgradient TWIS Issues

KEMC's characterization of the hydrogeology in the TWIS area is poor. Because of the lack of important characterization information, KEMC is unable to accurately identify the geologic setting, the extent of the hydrogeologic units in the TWIS area, or even the direction of groundwater flow. The major hydrogeologic characterization issues include:

- No boreholes or groundwater monitoring wells were completed in the area from the TWIS discharge point to KEMC's expected venting location. Without this essential information, it is impossible to generate a realistic cross-section of the hydrostratigraphic units in the TWIS area or reliable groundwater contours and flow directions. Available evidence suggests that Quaternary deposit stratigraphy in the TWIS area is complex and significantly different from other areas tested by KEMC to the west/southwest. The very limited available hydrogeologic data suggest that the current natural groundwater flow direction from the TWIS area could be to the north, to the east, or to the south. Additional wells are required to better define the groundwater flow direction.

- The cross-sections provided by KEMC do not accurately reflect geologic information from borehole logs; in particular, important information showing the presence of low-permeability strata well above the water table was not transferred to the cross-sections. These low permeability layers will likely cause mounding of the discharge at the ground surface.

- KEMC conducted one "specific capacity" test in the TWIS area to characterize the hydraulic properties in one zone (D zone) of the Quaternary deposit aquifer. These types of tests are inappropriate to use in such a complex aquifer system and will not provide reliable information on hydraulic properties. KEMC's use of the test is additionally flawed because most of the method's requirements were not met.

- The standard type of test to use for estimating hydraulic properties is a multiple-well aquifer pump test. KEMC conducted only one multiple-well pump test to characterize hydraulic properties in the aquifer units underlying the TWIS. The test was too far away [> 3,000 feet (ft) from the TWIS area]. In addition, the stratigraphy of the test area differs dramatically from that of the TWIS. In the test area, silt and clay layers (B and C zones) are up to 90 ft thick and occur below the water table. In the TWIS area, these same units are above and below the water table, are much thinner, and are inverted in some cases (e.g., C zone lies above the B zone). Because of these shortcomings, the methods KEMC used to characterize the hydraulic properties of the TWIS aquifer will not provide accurate information on the behavior of the TWIS discharge in the groundwater system.

KEMC's prediction of groundwater flow direction ignores the existing hydrogeologic information and is highly uncertain for the following reasons:

- KEMC assumes, based on inadequate information, that groundwater will flow in a northeasterly direction from the TWIS. However, KEMC's own cross-sections through the TWIS indicate very high gradients toward the southeast, or 90 degrees from the direction KEMC indicates on its inferred groundwater level contour maps.

- The Quaternary aquifer thickens and the bedrock surface slopes to the east/southeast, which is consistent with the strong gradients to the east-southeast shown on KEMC's cross-sections. Yet KEMC assumes that groundwater flows to the northeast, despite having no wells in this "downgradient" direction.

- Our model shows the major groundwater flow direction to the east/southeast, mounding of TWIS discharge at the surface as a result of "ponding" on lower permeability strata, and changes in aquifer thickness and groundwater flow directions in response to dikes. Flow to the east/southeast would ultimately be directed to the Yellow Dog River basin. KEMC has not considered the potential impact of TWIS discharge on the Yellow Dog River basin.

KEMC failed to consider the effect of major hydrogeologic basin features (e.g., dikes, faults, major surface drainage features) on groundwater flow conditions in the TWIS discharge area and in areas potentially affected by this discharge.

- A major dike occurs directly beneath the TWIS. This feature can drain groundwater from the overlying glacial aquifers to the underlying bedrock aquifer. The dike is oriented southeast, and groundwater can easily flow along the elongated brecciated margin of the dike in a southeastern direction, rather than to the northeast as KEMC assumes. Groundwater flow to the southeast is consistent with the strong groundwater gradients shown on KEMC's own cross-sections through the TWIS.

- KEMC has not considered the potential for movement of the TWIS discharge into the bedrock aquifer and has no wells in the bedrock in the TWIS area. KEMC failed to consider the effects of significant low permeability strata in the unsaturated zone beneath the TWIS. These strata were encountered in all but two of the nine borehole logs in the area. We conducted simple two-dimensional unsaturated zone flow modeling using the available information from the logs. Results from the modeling showed that infiltrating discharge from the TWIS will mound up to the ground surface beneath the TWIS, even when using KEMC's unreasonably low assumed mine inflow rates. Our modeling also shows that the degree of mounding above low-permeability material beneath the TWIS depends to a large degree on the lateral extent and configuration of the low permeability material. KEMC has not characterized the extent or configuration of these low permeability strata.

The proposed design of the TWIS groundwater monitoring well network is flawed because it does not account for the effects of shallow low permeability material in the unsaturated zone beneath the TWIS, the magnitude of rising water levels in the Quaternary glacial aquifer, or the direction of groundwater flow. More specifically:

- KEMC proposes to screen monitoring wells (using 10-foot screens) across the current water table. However, even their own analysis shows that discharge at the TWIS will cause water levels to rise by tens of feet. Post-discharge monitoring wells must be screened at higher levels in the aquifer to capture water discharged at the TWIS.

- The prevalence of shallow low-permeability material well above the water table in all but two of the nine boreholes beneath the TWIS will cause infiltrating TWIS discharge to mound over these units. As a result, wells screened over the current water table directly beneath the TWIS will likely miss most if not all of the infiltrating TWIS discharge. At a minimum, KEMC should have proposed a monitoring network that screens across these important low permeability zones.

- As TWIS discharge infiltrates beneath the TWIS and then mounds up over low-permeability units, it will start to flow laterally. Lateral flow will continue until the low permeability material pinches out. Whether the mounded discharge water actually reaches the current water table depends on the three-dimensional configuration, lateral extent, and hydraulic properties of the low-permeability strata. This stratigraphic, hydrologic, and geotechnical information must be collected and analyzed before a protective monitoring system can be designed.

- If the groundwater flow is indeed to the east-southeast, more monitoring wells are needed to the east and southeast of the TWIS, and monitoring of surface water to the east and southeast of the TWIS should also be added to the monitoring program.

Unless U.S. EPA requires compliance with relevant health-based water quality standards at the point of injection into the USDW, the only discharge standards that will apply are the State's groundwater discharge permit limits. Even though the MDEQ permit limits are similar to federal drinking water standards, very few of the limits are applied at the point of injection and, therefore, they are not protective of the USDW. The MDEQ groundwater discharge permit is not protective of groundwater quality for the following reasons:

- Effluent limits and reporting conditions are not protective of the USDW. The MDEQ permit has a condition for notification of changes in discharge that, because of the lax reporting requirements, allows the exceedence of a number of drinking water standards (antimony, cobalt, lead, ammonia, and thallium) in the effluent for periods of weeks to months. During this extended period of time, the contaminated effluent will be discharging at a rate of ~ 320 gpm into a USDW aquifer that has very little capability of removing contaminants or otherwise reducing the impact to downgradient groundwater.

- Similarly, downgradient limits are not protective of the USDW. Downgradient permit limits for antimony, arsenic, beryllium, boron, cadmium, cobalt, lead, nickel, ammonia, nitrate, and thallium exceed health-based state drinking water standards, maximum contaminant level goals, or Lifetime Health Advisories. Our analysis shows that the discharge will likely violate the prohibition of fluid movement because the expected effluent concentrations and the permit limits are less protective than relevant state and federal drinking water standards, goals, and advisories.

- KEMC's new information on groundwater quality in the vicinity of the TWIS demonstrates that water quality is good in the A and D zones of the aquifer, confirming that the USDW contains high quality water. Constituent concentrations in A zone groundwater are very similar to those in the upstream mainstem Salmon Trout River. The low alkalinity and hardness values in the shallow aquifer, into which the TWIS discharge may flow, suggest that interactions of the discharge with the aquifer material will not provide buffering or hardness and that the aquifer cannot be relied upon to attenuate contaminants released from the TWIS. It is therefore imperative that contaminant concentrations are controlled at the point of discharge from the WWTP and injection into the USDW from the TWIS.

The MDEQ'groundwater discharge permit is not protective of surface water quality. Although the UIC rules do not direct a UIC permit applicant to address surface water impacts, the groundwater that discharges at the TWIS will vent to the surface water in a relatively short distance. MDEQ's effluent and downgradient permit limits allow violations of surface water / groundwater-surface water interface (GSI) standards for barium, beryllium, cadmium, chromium, copper, nickel, silver, and zinc. For example, allowable groundwater zinc concentrations downgradient of the TWIS are over 18 times higher than the surface water/GSI standard at 50 mg/L hardness. The MDEQ permit limits, therefore, do not provide an adequate early warning system for surface water.

In summary, our analysis finds that U.S. EPA should deny KEMC's UIC permit application for the following reasons:

- KEMC has not adequately characterized the hydraulic properties or the stratigraphy of the Quaternary aquifer system beneath and downgradient of the TWIS. This lack of hydrogeologic characterization makes it impossible to identify the potential impacts to the USDW. In addition, the lack of characterization makes it impossible to design an effective monitoring system that will be protective of the USDW in the vicinity of the TWIS.

- KEMC does not have a viable contingency plan for handling excess water volume from underground mine. If water volumes are several factors to an order of magnitude higher than KEMC predicts, the only options for handing the excess water are shutting down the mine, adding the water to the underground mine or the development rock storage area, or discharging to surface water. Excess inflow from the mine would require treatment, and storage in the mine or the development rock is only a temporary solution. Discharge to surface water without treatment is not an option because KEMC does not have a surface water discharge permit, and the discharge would require substantial additional treatment to meet the more stringent surface water standards.

- The discharge will likely violate the prohibition of fluid movement because the expected effluent concentrations and the MDEQ permit limits are less protective than relevant state and federal drinking water standards, goals, and advisories. KEMC's ability to treat the discharge to levels that would meet the relevant standards is highly uncertain and the treatment process has never been adequately tested using solutions that are representative of WWTP inflows from the mine.

# 1. Introduction

This report addresses technical concerns related to Underground Injection Control (UIC) permitting of Kennecott Eagle Mineral Company's (KEMC's) Eagle Project, a proposed nickel-copper mine in the Upper Peninsula of Michigan. The report is prepared on behalf of the Keweenaw Bay Indian Community (KBIC).

The aquifers that will be impacted by KEMC's discharges are protected underground sources of drinking water (USDWs) because they: contain a sufficient quantity of groundwater to supply a public water system; contain fewer than 10,000 milligrams per liter (mg/L) total dissolved solids (TDS); and have not been declared exempted aquifers under the UIC program (Honigman Miller Schwartz and Cohn, 2006). Our analysis shows that KEMC has seriously underestimated the potential impacts to the USDWs in the treated water infiltrations system (TWIS) area. Our findings show that the wastewater treatment plant (WWTP) and TWIS designs are inadequate because (1) influent volume to the WWTP and the TWIS will be greater than predicted, (2) influent chemical concentrations to the WWTP and the TWIS will be higher than predicted, and (3) KEMC does not have an adequate contingency plan to handle either of these conditions. In sum, we find that the true impacts of TWIS discharge on the USDW have not been evaluated by KEMC.

## 1.1 Information Reviewed

A large body of technical information exists about the potential impacts of the mining operation on the environment. KBIC and the National Wildlife Federation (NWF) submitted two reports on geochemical and hydrogeologic issues related to the Eagle Project (Stratus Consulting, 2007a, 2007b). In addition, there was a three-month hearing before the Michigan Department of Environmental Quality (MDEQ) in 2008 that produced lengthy testimony on issues related to the mine and the TWIS. Selected testimony from the hearing is included in the appendices.

In this report, we summarize information presented in the Stratus Consulting reports and the hearing on issues related to impacts of the proposed Eagle Project on USDWs in the TWIS area. We also reviewed recent information submitted by KEMC at the request of U.S. EPA Region 5 (KEMC, 2008a, 2008b, 2008c, 2008d). The more recent KEMC information addressed the continuity and permeability of the clay layer in the Quaternary aquifer near the TWIS; groundwater quality for new wells located in the Quaternary aquifer closer to the TWIS; and the potential for releases of contaminants from fine-grained aquifer material as a result of TWIS discharge (see U.S. EPA, 2008). As part of our analysis, we also reviewed the Cadmus reports prepared for U.S. EPA (Cadmus, 2008a, 2008b).

## 1.2 Predictions and Review Overview

One of the main technical issues we highlight in the report is the lack of characterization of the Site. The predictions of impacts to the environment rely on adequate collection of data and site characterization – and realistic conceptual models that build on the available data (Figure 1.1). This process is described in a recent National Research Council report by Neuman and Wierenga (2003). Our review finds that there are major technical shortcomings with each step in the process shown in Figure 1.1 as they relate to KEMC's Eagle Project.

Assessing realistic potential impacts to the shallow drinking water aquifer from TWIS discharge requires a thorough understanding of several interrelated hydrogeologic and geochemical issues, including the current and post-discharge groundwater flow systems; water quality entering the

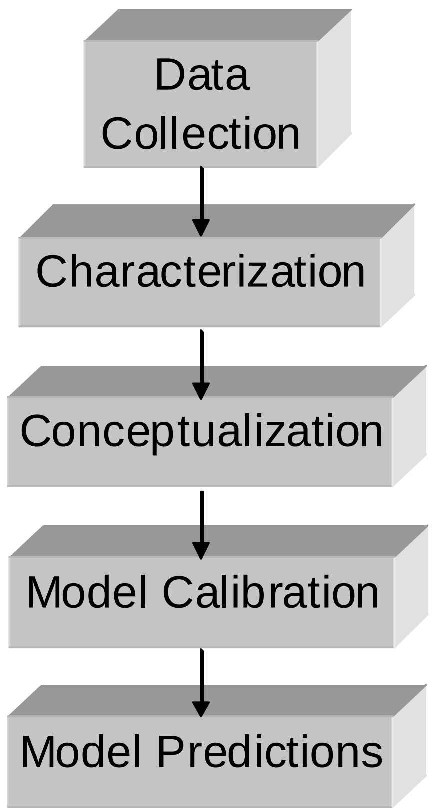


**Figure 1.1. Flow chart describing steps for data collection, characterization, conceptualization, and modeling of hydrogeologic systems.**

Sources: Anderson and Woessner, 1992; Fetter, 2001; ASTM, 2002.

treatment plant and the quality of the treated discharge; and the behavior of TWIS discharge in the aquifer. Each of the chapters in the report address both hydrogeologic and geochemical issues. Chapter 2 addresses inflows to the underground mine and the TWIS. Chapter 3 contains a discussion of WWTP issues, and Chapter 4 addresses hydrogeologic and geochemical issues downgradient of the TWIS.

# 2. Inflow to the Underground Mine and the Waste Water Treatment Plant

The vast majority of water discharged at the TWIS ultimately derives from inflow of bedrock groundwater to the proposed underground mine. KEMC relied on mathematical modeling (using FEFLOW, a groundwater flow model; Golder Associates, 2006) to predict flow volumes from the mine to the TWIS. KEMC has significantly underestimated the amount of groundwater inflow to the mine and has therefore underestimated the amount of flow from the TWIS to groundwater at the Eagle Project site (the Site). This underprediction represents a major problem related to the design of the treatment plant and the TWIS, and the impacts of TWIS discharge to USDW.

KEMC's estimates of mine inflow are too low for the following reasons:

1. Hydrogeologic characterization and conceptualization were poor and misleading

2. Modeling did not include or consider major water-conducting structural features present throughout the area

3. Modeling assumed that faults did not continue into the upper bedrock – only lower bedrock

4. The effects of crown-pillar failure or the increase of hydraulic conductivity due to dilation of the rock mass were not evaluated as a contingency or as part of the model

5. The effects of mine workings, including the access tunnel, were not considered in the model.

In fact, the groundwater inflow rates simulated by the model were not high enough to dewater the access tunnel and the lower portions of the mine. We modified Golder's FEFLOW model using more realistic assumptions and found much higher predicted groundwater inflows. The higher inflows are similar to inflow rates for existing hardrock underground mines in the area. KEMC did not consider inflow rates from local mines in its modeling effort.

## 2.1 Hydrogeologic Characterization and Conceptualization

The hydrogeologic system in the vicinity of the proposed Eagle Project is comprised of the bedrock aquifer (upper and lower units) and the overlying Quaternary unconsolidated glaciofluvial aquifer. The bedrock aquifer is complex in terms of its geology (e.g., igneous and metasedimentary formations and dikes are present), structural characteristics (e.g., regional and local dikes and faults are present), and groundwater quality (e.g., lower ionic-strength groundwater overlies a brine of varying salinities). The characterization deficiencies in the bedrock aquifer system include a lack of identification of faults and dikes; a low number and poor placement of wells for hydraulic testing; and poor delineation of the upper and lower bedrock zones. In addition, no groundwater potentiometric surface maps exist for the upper or lower bedrock aquifers. These deficiencies affect groundwater flow into the mine, flow to the WWTP, flow to the TWIS, and ultimately the water discharge of contaminants to USDW.

### 2.1.1 Bedrock flow system

#### Inadequate number of boreholes

The number and locations of boreholes are inadequate to characterize the structurally complex bedrock hydrogeology in the area. Figure 2.1 shows the location of bedrock wells and boreholes. The same number of boreholes was used to characterize the smaller area affected by dewatering and the larger modeled area [over 87 square kilometers ($km^2$)]. KEMC apparently drilled many more “exploratory” boreholes but did not provide the information from these boreholes for review or use it to develop the geologic framework for the modeling of mine inflow.

#### Characterization of faults and dikes

The bedrock geology in the area impacted by mine dewatering is complex, yet KEMC failed to investigate and incorporate several major structural features into their overly simplistic conceptualization of this system. For example:

- *Faults*: Major faults, extending for miles, have been mapped through an area potentially impacted by dewatering and the modeled 87-$km^2$ area (see Figure 2.1). Faults generally tend to trend north-south. These faults were mapped by KEMC’s own geologists but were largely ignored in their characterization of the bedrock geology and the Golder model. Klasner et al. (1979) also mapped faults throughout the area, and their fault locations, extent, and orientations are generally consistent with those of KEMC’s geologists.
    - Klasner described a 500-meter (m) wide fault-zone trending northwest-southeast, just east of the mining area, that actually goes through the proposed access tunnel. KEMC did not describe or consider this major fault zone in their characterization of bedrock geology.

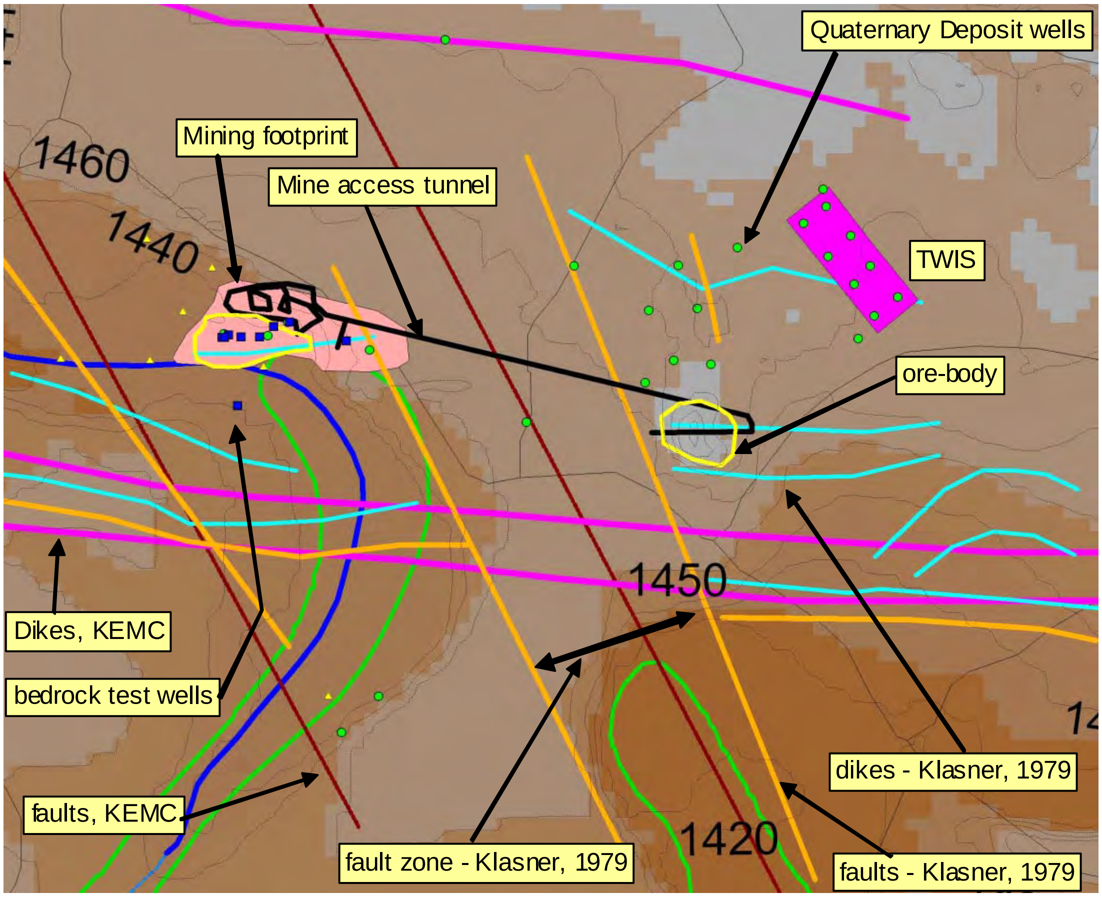


**Figure 2.1. Location of bedrock test wells (blue squares) relative to major structural features (dikes and faults labeled), mining footprint, access tunnel, and Salmon Trout River (dark blue line).** Light gray lines represent surface elevations (in feet). The curved green lines delineate wetland areas.

Source: Klasner et al., 1979.

- In their modeling, Golder included faults in the lower bedrock but did not extend them into the upper bedrock (Foth & Van Dyke, 2006a, Vol. 2, App. B-4, Figure 3-1). Limiting the vertical extent of faults in this way is unrealistic (if anything, faults are more likely to exist in shallower bedrock). It is also highly biased because it will severely underestimate the impacts of dewatering to the upper bedrock, the overlying Quaternary unconsolidated material, and the Salmon Trout River. Consequently, the model will under-predict inflow rates during mining.

- *Dikes*: Numerous dikes that extend through the area (mainly trending east-west, as shown in Figure 2.1) likely influence the flow through the bedrock aquifer. Dikes typically act as low-permeability features and prevent or minimize cross-flow. However, they often have high-permeability brecciated zones oriented parallel to their planes (Kruseman and de Ridder, 1991). KEMC's own cross-sections acknowledge their existence (see, e.g., Foth & Van Dyke, 2006a, Vol. 2, App. B-5, Figures 15 to 18), but KEMC made no attempt to characterize these features and their potential influence on natural groundwater flow, or on infiltrating TWIS discharge. Cadmus (2008a, pp. 17, 21) correctly pointed out that KEMC did not consider the effects of dikes in their analytical or numerical analysis (Foth & Van Dyke, 2006b, App. E-2 and E-3, respectively). The presence of dikes can significantly reduce flows perpendicular to them, but it can also dramatically increase flows along them. This could dramatically increase mine inflows. In fact, the Salmon Trout River, as it flows to the north, abruptly changes direction when it intercepts the Peridotite dike, and then realigns itself parallel to the dike. The river itself provides an ample supply of water for inflow into the mine via the dike, yet KEMC never assessed this major hydrogeologic feature.

**Hydraulic testing**

KEMC modeled drawdown over a wide area that included several major structures such as faults and dikes (see Figure 2.1). However, drawdown was modeled based on hydraulic testing of the bedrock that was too localized and covered only a small area, largely within the ore-body, as shown in Figure 2.1 (green squares). As shown in Figure 2.1, only one bedrock testing well was located outside of the immediate ore body area. A much wider area should have been tested, including the area that will potentially be affected by groundwater drawdown from mine dewatering. There were two phases of hydraulic testing: one in 2005 that included four slug tests; and one in 2006 that only included one multi-well pump test (with well 084 as the pumping well). The results of this pump test are shown in Figure 2.2.

No bedrock wells were monitored north or south of the pumped wells (107 and 084; see Figure 2.1) e.g., in the area of the proposed underground workings or south of the Salmon Trout River. Testing in these areas would have helped estimate the extent of drawdown and hydraulic communication across the river and across a known dike and possible fault.

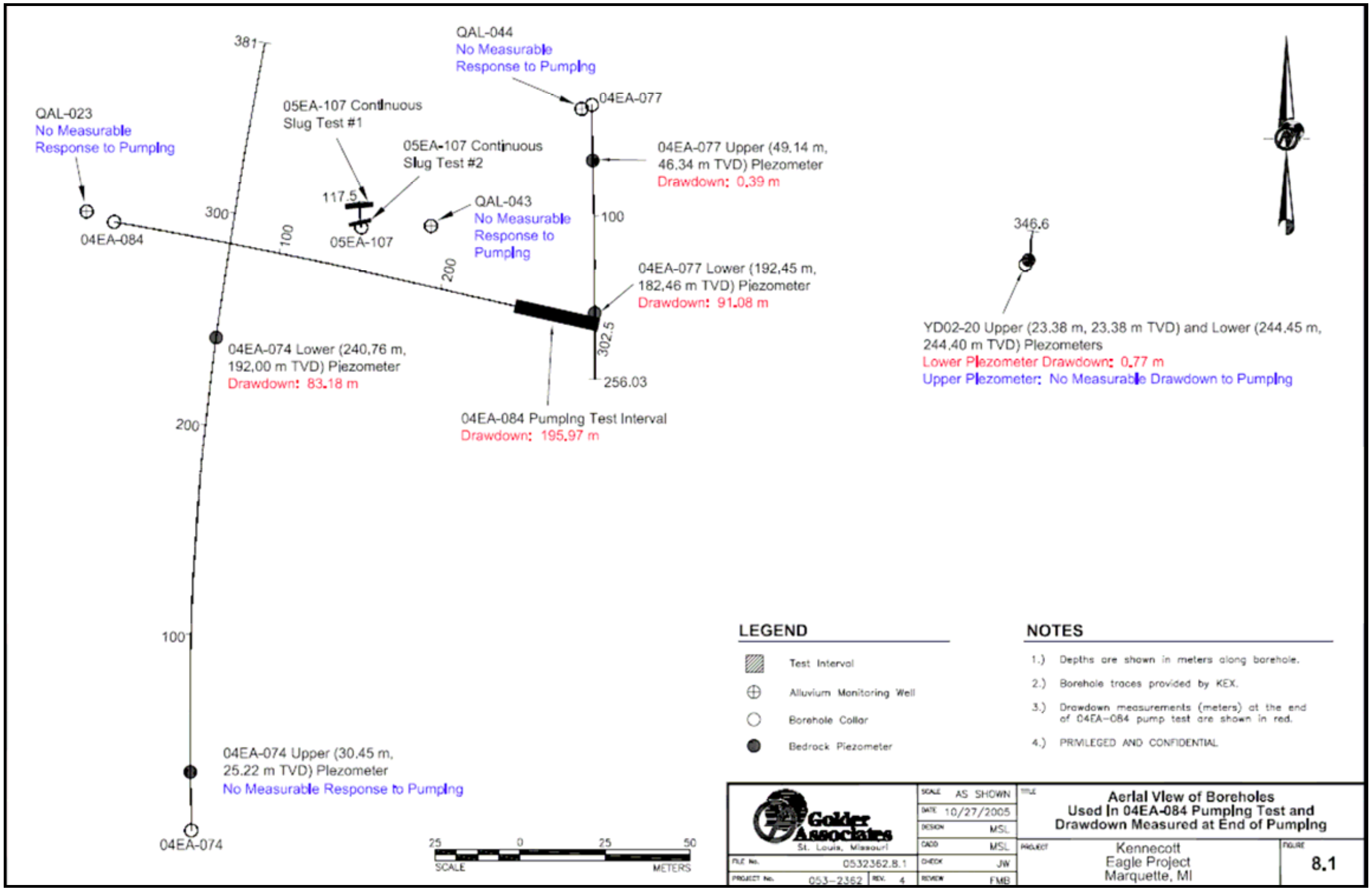


**Figure 2.2. Location of wells and response to hydraulic testing.**

Sources: Foth & Van Dyke, 2006a, Vol. 2, App. B-3; Golder Associates, 2006, Figure 8.1.

Wells east and west of pumped well 084 showed a clear and large response to pumping. Wells 074 and 077 showed a drawdown of 83.2 and 91.1 m, respectively (see Figure 2.2). Given this large response, wells should have been tested that were much farther away in all directions from the pumping well, including across known faults and dikes, to estimate the complete extent of response in the bedrock aquifer. Only one bedrock test well was monitored just outside and east of the immediate ore-body area (YD02-020), yet KEMC predicted that the areal extent of mine dewatering (more than 1 foot at more than a mile from the ore-body – see Foth & Van Dyke, 2006a, Vol. 2, App. B-4, Figures 9.4 and 9.5) will extend far beyond the distance to this well. The well intercepts several major structures (dikes and faults) that KEMC did not hydraulically test. Therefore, KEMC's predicted mine inflow and impacts to groundwater levels in the bedrock and Quaternary aquifers beyond the area of hydraulic testing are highly uncertain.

KEMC did not consider faults and dikes in test well placement. It is standard hydrogeologic practice to evaluate the hydraulics of these features (Kruseman and de Ridder, 1991). When these types of features are present, pumping, monitoring, and response wells should be placed on either side of the features to test whether water across the features is in hydraulic communication. KEMC's test well placement was too localized (over the ore-body), and the locations of the pumped bedrock wells (107 and 084; see Figure 2.2) did not adequately test major water-conductive features over the area that may be affected by mine dewatering (see Figure 2.1).

KEMC assumed that the fault in the lower part of well 084 (257.7 to 260.3 m) is the primary water-conductive feature within the ore body and surrounding area. This is inconsistent with faulting mapped in the area by various parties that show additional faults (see, e.g., Figure 2.1). KEMC assumed that the fault in well 084 has a limited geographic extent. Their own analysis suggests that the fault in 084 at 257.7 m is likely connected to a more water-conductive feature at some distance (Appendix A).

Other deficiencies related to hydraulic testing include the length of the pump test and the use of slug tests. The length of the single pump test (seven days) was too short to characterize such a large rock mass. Pump tests should have been conducted for a much longer period of time (e.g., a month) to better assess the nature of increasing transmissivity observed in pumped well 04EA-084 (Figure 2.3). At the end of the seven-day pump test, the results showed an increase in transmissivity [see Figure 2.3, shown as a downward curvature in the measured data (blue diamonds)]. This increase in permeability clearly indicates that a water-conductive feature exists at some distance from the pumping well. However, the pump test was stopped right after this anomaly occurred. The test should have been conducted long enough, and with better spatial distribution of monitoring wells around well 04EA-084, to fully assess the nature of this water-conductive feature, and likely others. KEMC should have also tested the potential for water flow along the dike during this test.

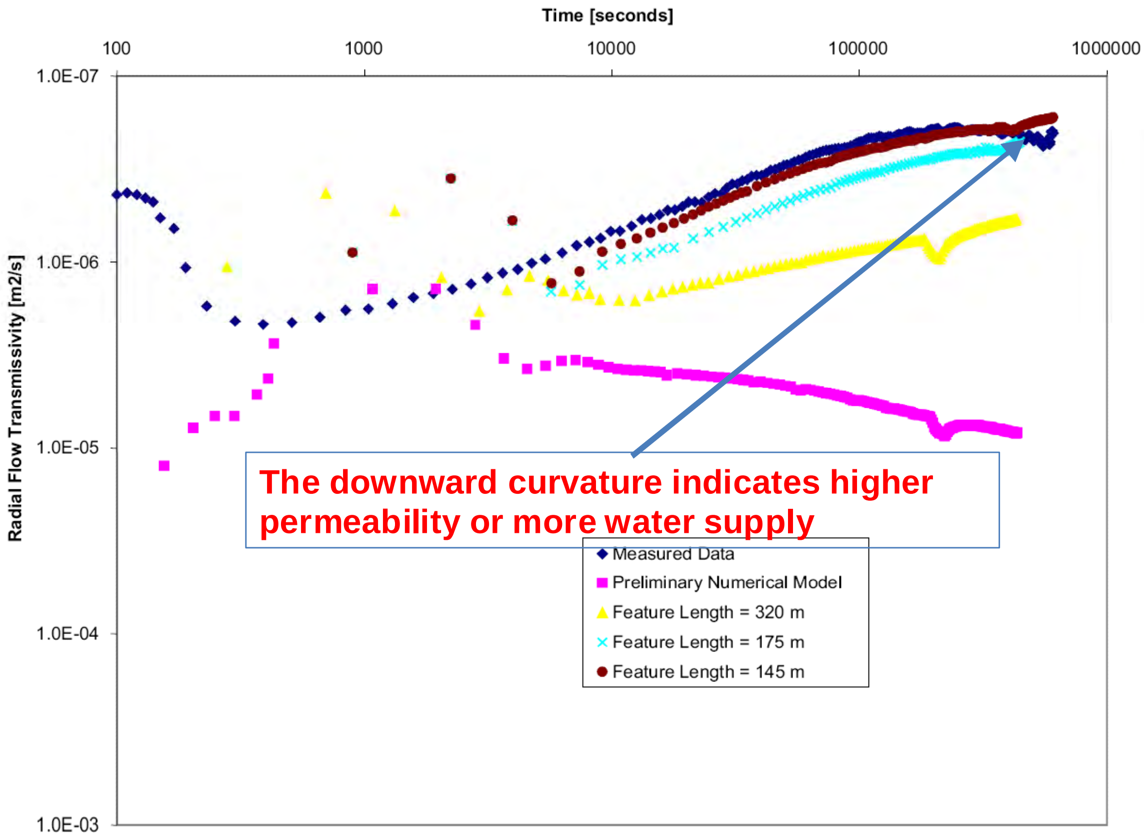


**Figure 2.3. Transmissivity vs. time during the pump test at well 084.** Transmissivity increases from top to bottom on the y axis.

Source: Modified from Foth & Van Dyke, 2006b, Vol. 2, App. B-4, Figure 8.4.

Figure 2.3 clearly shows that the simulated drawdown for the conceptual model with 145-m faults (brown circles) does not reproduce the important trend of increasing transmissivity in the measured data (blue diamonds) near the end of the seven-day test. The data indicate that the transmissivity beyond seven days would continue to increase, yet results of the 145-m simulation shows transmissivity decreasing abruptly before the end of seven days. If KEMC had conducted a longer pump test (e.g., one month) and attempted to match this later portion of the test, they would have had to significantly increase fault lengths. Results of their pump testing do not provide an adequate basis for assuming that the 145-m long faults are vertical or oriented north-south. In fact, the monitoring wells experiencing the most drawdown during the 04EA-084 pump test were actually located to the west (well 04EA-074) and east (wells 04EA-77, YD02-20).

KEMC did not monitor the lower bedrock north and south of the pumped well (e.g., on both sides of the Peridotite dike), yet they assumed in their subsequent FEFLOW modeling that the 145-m fault is oriented north-south. They should have provided better spatial monitoring of the upper bedrock and overburden over the entire mining area given the complexity of hydrogeology in this area.

One slug test was performed in well 107 (see Figure 2.2 for location of the well). Slug tests are known to produce less accurate and very localized results compared to long-term pump tests, and the results are biased toward underestimating true permeability (Butler and Healey, 1998).

**Characterization of "upper" and "lower" bedrock**

KEMC distinguishes the "upper" and "lower" bedrock based on differences in groundwater quality. The lower bedrock contains water with high solute concentrations and specific conductance (SC) (e.g., sodium = 970 mg/L and chloride = 2,010 mg/L), and the upper bedrock contains fresh water (e.g., sodium = 21-80 mg/L and chloride = 1.2-97 mg/L; Foth & Van Dyke, 2006a, Vol. 2, App. F and G, Table 4-1). KEMC defines the "contact" between the upper and lower bedrock as 90 m below the ground surface (Foth & Van Dyke, 2006b, Vol. 2, App. B-2, p. 32). However, KEMC relies on a single groundwater sample from well 084 to determine the depth of upper-lower bedrock contact, and consequently the delineation of the "upper" and "lower" bedrock across the Site and the modeled area is poor. Therefore, this "contact" between the upper and lower bedrock is largely a difference in water quality in the bedrock aquifer, rather than some physical difference in the bedrock. The rock type and age of this intrusion are continuous and likely homogeneous, with the possible exception of some weathering that extends down from the top of the bedrock.

The depth to saline water in the mine project area is important because it defines the type of background bedrock groundwater entering the mine as inflow – and thus the types of treatment required at the WWTP. Although the proposed mine would be entirely in the lower bedrock aquifer, the underground workings would go through the upper and the lower bedrock zones (Sainsbury, 2007). Blasting during mine operations could easily increase fractures that would connect the upper and lower bedrock zones and bring more highly saline water into the underground mine. The possible ranges of salinity of mine water were not modeled or considered in planning the treatment plant operations.

Table 2.1 shows the depth to saline water in six bedrock wells in the proposed mine area. The variability in electrical conductivity (EC) with depth in all six boreholes implies that the system does not fit the simple conceptual model proposed by KEMC [i.e., > 90 m total vertical depth (TVD) is the isolated lower bedrock zone]. As shown in Table 2.1, wells 054, 083, and 084 have water with low SC values to a depth of ~ 200 m, or well below the 90-m depth proposed by KEMC as the upper-lower bedrock contact. These wells are located in the western central part of

**Table 2.1. Depth to saline water in the Eagle ore body area.** Note: KEMC modeling assumes that the depth is 90 m.

| ~ Location in ore body (see Figure 2.5) | Well | Depth (m) where EC > 1,000 µS/cm | Highest EC (µS/cm)/depth (m) | Notes |
|---|---|---|---|---|
| West central | 04EA-54 | ~ 175 m | 10,000 / 275 m | |
| Northeast | 04EA-73 | ~ 25 m | ~ 3,000 / 215 m | Lower EC below this |
| East northeast | 04EA-77 | ~ 25 m | ~ 1,500 / 254 m | Lower EC below this |
| West central | 04EA-83 | NA | 500 / 200 m | Always < 1,000 µS/cm (max. depth of borehole = 240 m) |
| West central | 04EA-84 | ~ 230 m | 2,000 / 260 m | Lower EC above and below this |
| Central | 04EA-47 | 0 m | ~ 12,000 / 210 m | ~ 2,000 µS/cm at 0 m, but increases at 100 m to ~ 4,000 µS/cm |

EC 5,000 µS/cm = ~ 2,500 mg/L TDS, so 1,000 µS/cm = ~ 500 mg/L TDS. The secondary maximum contaminant level (SMCL) for TDS is 500 mg/L.

Source: Foth & Van Dyke, 2006b, Vol. 2, App. B-2.

the ore-body (see Foth & Van Dyke, 2006b, App. B-2, Figures 3-1 through 3-6). Trends in SC with depth in well 054 are shown in Figure 2.4. In contrast to these wells with greater depth to saline water, well 047 shows water with ~ 2,000 microSiemens per centimeter (µS/cm) close to the ground surface. The same well shows a dramatic drop to < 1,000 µS/cm for last 150 feet (ft) in lower bedrock that cannot be attributed to dilution with drilling fluid, as KEMC has suggested. The implications for upward movement of brines as a result of fracturing and blasting during mining – or the implications for variation in inflow water quality to the WWTP – were not considered at all by KEMC.

KEMC did not characterize the spatial variability of groundwater density in the bedrock flow system. Knowledge of this spatial variability of groundwater density is required to estimate groundwater flow directions, which in turn are required for developing an adequate conceptual model of flow for the bedrock flow system. The FEFLOW bedrock flow model KEMC uses to estimate mine inflow is flawed because it did not consider density-dependent flow conditions, and it did not attempt to reproduce actual field conditions. This affects the model's ability to predict mine inflows and the degree to which the natural system is impacted by dewatering. An evaluation of this information is standard practice and requires collecting adequate information on the spatial distribution of salinity/density in the field.

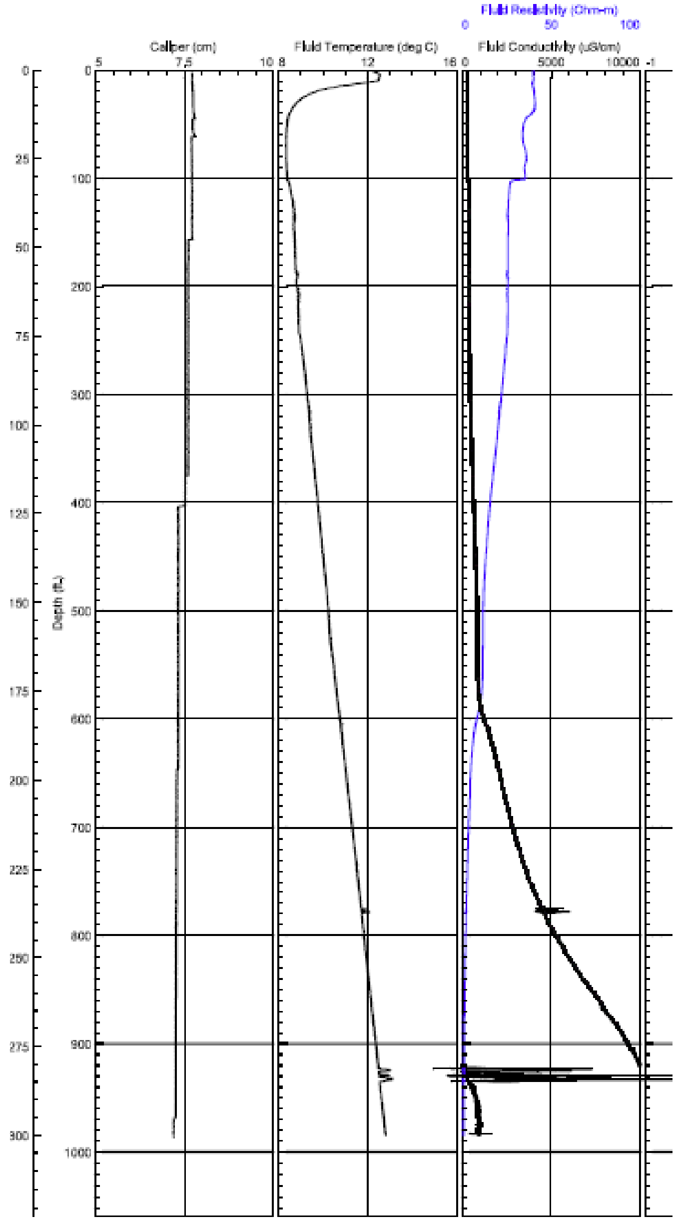


**Figure 2.4. Geophysical logs for well 04EA-54 showing the behavior of fluid conductivity with depth.**

Source: Foth & Van Dyke, 2006b, Vol. 2, App. B-2.

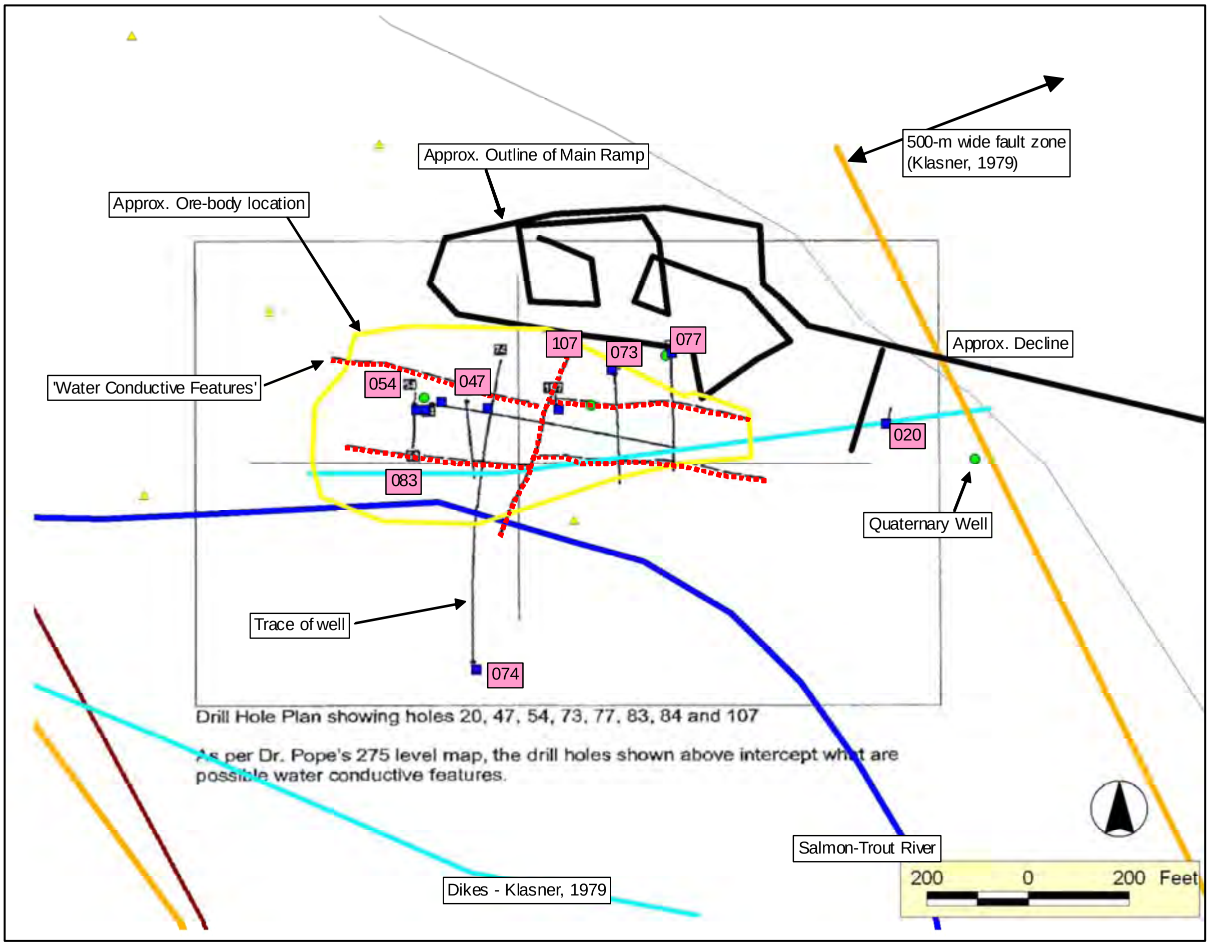


**Figure 2.5. Location map for boreholes used in Table 2.1.**

Sources: Based on Intervenor Exhibit 214: Drill hole trace map on Level 275 in the underground mine. (Appendix C); Klasner et al., 1979.

EC (which can be converted to density) information is available from geophysical logs (an example is shown in Figure 2.4), but KEMC suggested that these results were compromised by drilling fluids and fresh water flushing, and interpretation can only be qualitative (see Foth & Van Dyke, 2006b, Vol. 2, App. B-2, p. 12). Although this may be true, results from the EC logs (Foth & Van Dyke, 2006b, Vol. 2, App. B-2, Figures 3-1 to 3-6) are inconsistent with both KEMC's interpreted density profile and their conceptual model (Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Figure 10.2 and pp. 40-41), which suggests that TDS increases at the upper-lower bedrock interface. For example, EC logs for boreholes 04EA-047 and 04EA-054 (Figures 3-1 and 3-2) show much higher values [> 12,000 micro-mhos per centimeter (μmhos/cm)] than other logs and much higher values than represented by the maximum TDS of 3,990 in well 04EA-084 (Figure 10.2, App. B-3, EIA). Not characterizing the three-dimensional spatial variability in groundwater density and not considering density-dependent flow conditions in bedrock modeling of mine dewatering scenarios are serious flaws in KEMC's estimate of inflow rates and impacts to the natural system.

**Potentiometric surface and groundwater gradients**

KEMC did not determine groundwater elevation contours (or hydraulic gradients) in the bedrock aquifer, yet this information is necessary to conduct realistic modeling of the bedrock aquifer. No groundwater potentiometric surface maps were prepared for the upper or lower bedrock aquifers. No groundwater flow directions, velocities, hydraulic gradients, or three-dimensional flow paths were determined for the existing bedrock flow system over the impacted area.

KEMC has implied that there is no lateral groundwater flow in the bedrock aquifer (Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Section 10). However, the groundwater elevation in YD-20 (easternmost bedrock well), corrected for density differences, is ~ 2.5 m lower than in other wells in the area (see Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Table 10.1). This difference strongly suggests that the lower bedrock groundwater likely flows toward the east. Well YD-20 is located at the western edge of the 500-m wide fault zone mapped by Klasner et al. (1979) (Figure 2.5). In other words, this fault zone may be acting as a large drainage feature in the bedrock and causing the surrounding groundwater to drain into it. This fault zone may eventually drain into Yellow Dog River to the southeast. This anomaly was not investigated by KEMC but would likely be important in predicting the extent and magnitude of mine dewatering and TWIS discharge mounding and migration.

KEMC also concluded that there is essentially no vertical hydraulic gradient between the upper and lower bedrock aquifers (Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Section 10). In short, KEMC never determined how groundwater flows through the bedrock system, which is essential for estimating not only mine inflow, but how the natural system would be impacted by dewatering and TWIS discharge. Importantly, KEMC's assumption of no lateral or vertical groundwater flow in the bedrock implies that contaminants generated in the underground mine will not flow out of the mine after closure and affect USDW. This assumption underestimates the potential for both groundwater and surface water contamination and is not supported by the existing data. The lack of adequate hydrogeologic characterization of flow between the upper and lower bedrock, and laterally within each zone, makes estimates of mine inflow rates highly uncertain. Similarly, the extent and magnitude of impacts to bedrock and Quaternary groundwater and stream flow systems are also highly uncertain.

### 2.1.2 Quaternary deposit flow system

The Quaternary aquifer overlies the bedrock aquifer in most locations. The unconsolidated Quaternary aquifer contains five identified units: A through E. Units A and D are sandy aquifers; units B and C are considered confining zones, comprised mostly of silts and clays; and unit E is glacial till. In some locations, the Quaternary aquifer is missing, and the bedrock aquifer outcrops at the surface and is in direct hydraulic communication with the overlying Salmon Trout River.

**Number of wells for hydrogeologic characterization**

The number and location of wells in the unconsolidated aquifer are inadequate to assess the hydrogeologic characteristics of the aquifer, including the degree of hydrologic connection among the units (A through D) and between the glacial aquifer and the underlying bedrock aquifer (see Foth & Van Dyke, 2006b, Vol. 2, App. B-1, Figures 23 and 24 for a depiction of the Quaternary aquifer). More nested wells should have been placed in the immediate mining/access tunnel area, on both sides of Salmon Trout River, to better assess the natural flow conditions in the Quaternary aquifer, its interaction with the bedrock flow system, and how this system will be impacted by mine dewatering. More wells should have been located in the area most affected by mine dewatering, or within one mile of the mine (see Foth & Van Dyke, 2006b, Vol. 2, App. B-4, Figures 9.4 and 9.5). No assessment wells were located around the East Eagle Rock area (location of the East Eagle deposit), and only one unconsolidated aquifer well is located in the main Eagle ore body area (see Figure 2.1). Two figures in the Mine Permit Application (MPA; Foth & Van Dyke, 2006b, Vol. 2, App. B-1, Figure 13, and App. B-5, Figure 12) show areas where the glacial aquifer is absent (i.e., where bedrock outcrops at the surface), but they are inconsistent with each other, which highlights the poor characterization of important hydrogeologic features. The unconsolidated aquifer near this area should have been characterized in more detail, because this is an area where Salmon Trout River water could directly enter the bedrock flow system (e.g., along the Peridotite dike) and caused increased mine inflows that were not considered by KEMC. Monitoring wells should have been placed in the unconsolidated aquifer near where the unsaturated Quaternary material thins, and in areas where dikes may act as preferential pathways into the bedrock. These areas would have responded readily during the 04EA-084 well testing (Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Section 8).

**Stratigraphy**

The Quaternary deposit stratigraphy is poorly defined, especially in the area potentially impacted by mine dewatering. Better definition of the stratigraphy is critical to understanding how groundwater flowing through the Quaternary material above the dewatered zone interacts with the dewatered bedrock. Limited information from the geologic logs shows that the glacial-alluvial stratigraphy in the area is complex, and little effort has been made to assess how it changes in response to the elevated bedrock along the peridotite dike in the mine area, or to other dikes to the south and north of the mine area that are within the dewatering area, as predicted by Golder's model.

**Hydraulic testing**

The test methods that KEMC used to determine hydraulic conductivity values (i.e., slug tests, laboratory tests) for the different Quaternary deposit hydrostratigraphic units were unreliable, and the results from these tests are not representative of the area of interest. For example:

- Many of the hydraulic tests were either slug or laboratory tests. These methods are inexpensive and rapid ways to measure hydraulic properties, but they are generally not good indicators of in-situ effective hydraulic properties for an aquifer system. Typically, these methods return hydraulic conductivity values that are too low (Butler and Healey, 1998). Instead, multiple-well pump tests should have been conducted at numerous locations. KEMC's own consultants acknowledge that pump tests produce the most accurate data (see Foth & Van Dyke, 2006b, Vol. 2, App. B-5, Table 2 and App. C).

- Many of the wells completed in the unconsolidated material are screened over smaller intervals (e.g., 5 ft) than the full aquifer thickness. The small screened interval results in collection of hydraulic property data that are not representative of the entire aquifer.

Wells used for testing the extent of hydraulic communication between the A and D aquifer zones were located in areas far away from expected mine dewatering and TWIS discharge (see red symbols in Figure 2.6). The thickness of the confining zones (B and C) in the areas tested ranges from 61 to 87 ft, whereas the thickness in the mine area ranges from only 0 to 30 ft. The thickness of the confining B/C units is also much greater in the test area than beneath the TWIS, where it is assumed to pinch out completely. It is misleading to conduct tests in an area where the thickness of low permeability material between two aquifers is much larger than in the areas of interest. Testing conducted in areas where the B/C units are relatively thick erroneously leads KEMC to conclude that low conductivity sediments will severely limit the movement of groundwater between the A and D zones, and that the D zone acts as a confined aquifer in the test area. If the same testing were conducted in key areas of interest (near the ore-body, where bedrock outcrops at the surface, or near the TWIS where KEMC claims these units pinch out), these conclusions would be different. KEMC has made no attempt to conduct the appropriate testing in these key areas.

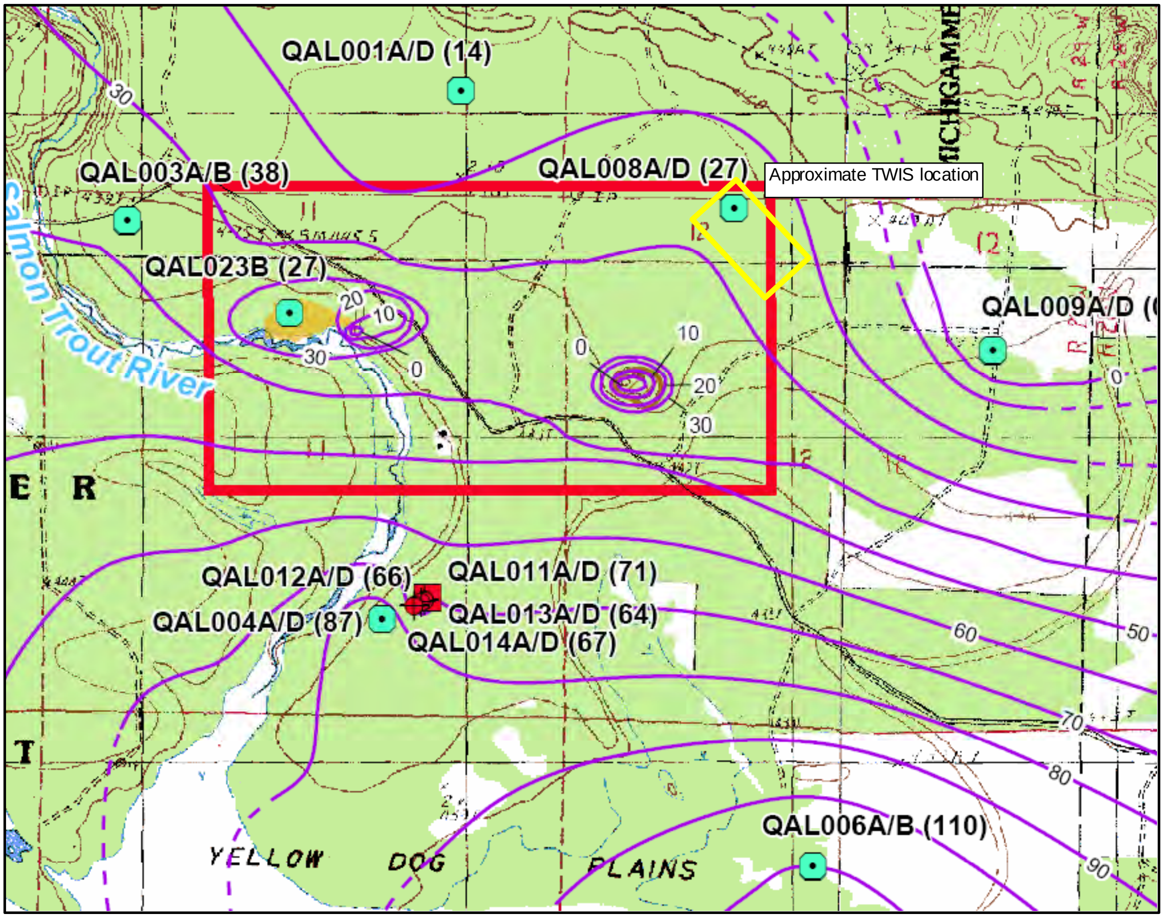


**Figure 2.6. Isopach (thickness) map (ft) of the B/C confining units and Quaternary aquifer monitoring wells, with zones indicated in well ID.** Wells in red were used for hydraulic testing.

Source: Foth & Van Dyke, 2006b, Vol. 2, App. B-5, Figure 12.

## Hydraulic communication with the bedrock aquifer

KEMC concluded that there is no hydraulic connection between the bedrock and the Quaternary aquifers. This conclusion implies that dewatering of the bedrock aquifer during mining would have no effect on water levels in the overlying Quaternary aquifer, and by extension, in the Salmon Trout River. However, the hydraulic tests upon which KEMC relied to reach this conclusion were flawed in the following ways:

- KEMC used results from the single bedrock aquifer pumping test to conclude that there was no response in the Quaternary aquifer.[1] However, the continuous slug test conducted in the upper bedrock (well 04EA-107) showed a clear response in the Quaternary aquifer (well QAL023; see Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Table 7.3 and Figure 7.25). These types of conflicting results should have encouraged further testing of the hydraulic connection between the bedrock and Quaternary materials, particularly in the zone predicted to be impacted by dewatering.

- The three Quaternary wells used to assess hydraulic communication with the bedrock aquifer do not adequately reflect the complexity in the mining area, the area impacted by dewatering (based on Golder modeling), or the 87-$km^2$ model area. The stratigraphy in the vicinity of the ore-body is complex and highly variable, as indicated by geologic logs and cross-sections through the area. The three wells used in the pump test do not target areas in the overburden most likely to experience drawdown from pumping in the lower bedrock.

- KEMC did not test the connections between the Salmon Trout River and the bedrock. The thickness of unconsolidated material is highly variable, especially over the ore-body, and in places does not exist (Figure 2.7). Figure 2.7 shows an absence of unconsolidated material at the ore body, extending for some distance beneath the Salmon Trout River. This figure clearly indicates that the Upper Bedrock aquifer is in direct contact with the river/wetland area, yet KEMC installed no monitoring wells in this area to test the degree of hydraulic connection between the river (or nearby areas where Quaternary deposits thin) and underlying bedrock zones. None of the groundwater flow models considered what likely represents a direct flow conduit from the river into the bedrock system. Under current natural conditions, this conduit may not manifest itself in a notable fashion, but under full mine-dewatering conditions, this area could act as a local drain for the nearby wetland and river.

- More appropriate testing locations should have been included, e.g., in areas along KEMC cross-sections where the D-zone aquifer lies directly over the bedrock, or where the glacial till (E-zone) is absent (e.g., see Foth & Van Dyke, 2006b, Vol. 2, App. B-1, Figure 28).

---

1. The pumped bedrock well was EA04-084 (in the ore body), and the monitored Quaternary wells were QAL023, QAL043, and QAL044 (see Foth & Van Dyke, 2006b, Vol. 2, App. B-3, p. 24).

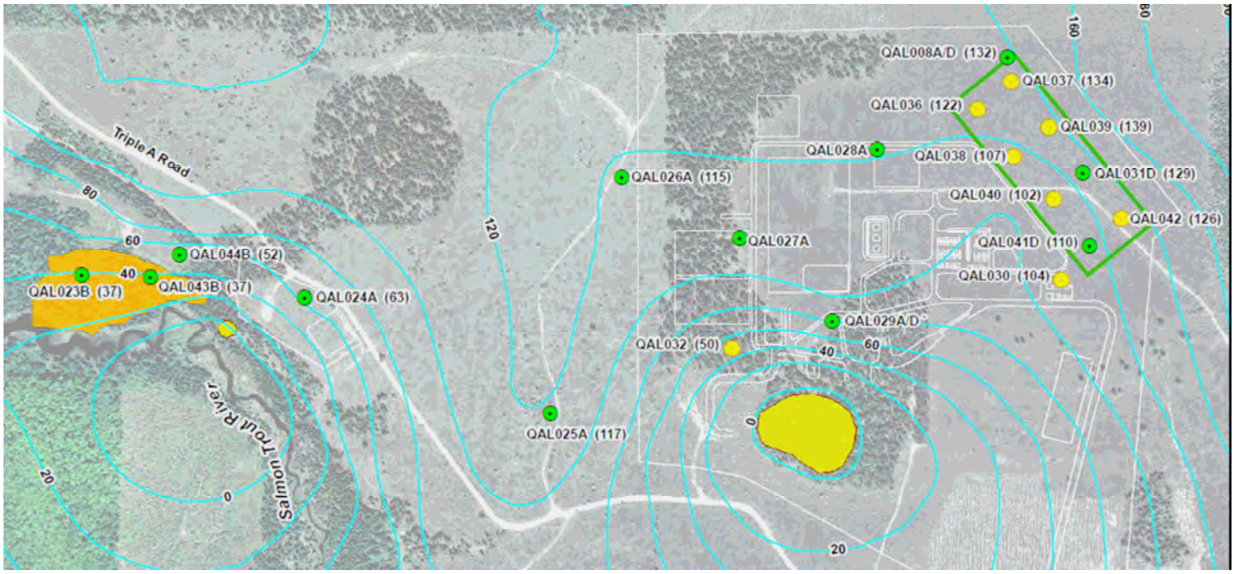


**Figure 2.7. Isopach (thickness) map of the Quaternary deposit.**

Source: Modified from Foth & Van Dyke, 2006b, Vol. 2, App. B-1, Figure 13.

## 2.2 Bedrock Model Development and Predictions

### 2.2.1 Mine inflow models – KEMC consultants

Golder created a preliminary and a revised FEFLOW model (Foth & Van Dyke, 2006b, Vol. 2, App. B4) to evaluate the effects of mine dewatering on bedrock groundwater levels and inflow of water to the underground mine. Golder's (Golder Associates, 2006) bedrock FEFLOW modeling has a number of deficiencies:

1. *Quaternary material was not realistically simulated*. Golder did not simulate flow in the saturated or unsaturated Quaternary material, although the FEFLOW model could have been used to do this. Instead, an overly simplistic boundary condition was used to simulate flow from the saturated Quaternary deposit material into the mine. None of the stratigraphic complexity of the deposit (variation in overall thickness and thickness of individual geologic units) or actual groundwater flow conditions were represented in the model.

2. *Salmon Trout River was not included in model*. The bedrock model did not consider the high potential for flows from the river to the dewatered bedrock zone through the brecciated zone of the dike that outcrops directly beneath the Salmon Trout River. Golder also did not consider the probable movement of river water into the mine through the bedrock faults or dikes that intercept the Salmon Trout River, as shown in Figure 2.1.

3. *The effect of saline water in the mine was not simulated*. Density-dependent flow effects were not simulated in Golder's mine dewatering model simulations, even though Golder points out that FEFLOW has this capability. It is even more surprising that they do not attempt to simulate density-dependent flow conditions to simulate their proposal for injecting fresh water into the mine during closure to speed post-mining filling of the backfilled underground mine. Golder should have also considered density-dependent flow conditions in their attempt to reproduce pump test results in well 04EA-084, which showed high salinity (see Foth & Van Dyke, 2006b, Vol. 2, App. B-3, Table 10.1).

4. *Poor model calibration*. Golder did not attempt to calibrate the bedrock flow model to actual bedrock groundwater level information, which is standard practice (Golder Associates, 2006). They should have used the density-dependent flow capabilities of FEFLOW to simulate actual variable density conditions observed within the bedrock. Instead, Golder developed and calibrated their FEFLOW model to the highly localized hydraulic testing data from the ore body area (04EA-084). Golder should have obtained groundwater levels, density, and hydraulic testing information from bedrock wells installed throughout the area potentially impacted by dewatering to calibrate their bedrock flow model. They could have used their preliminary model to determine this extent (~ 1 mile radius, where bedrock groundwater levels drop more than 1 foot).

5. *Groundwater inflow estimates will not allow the mine to dewater completely*. Golder used the FEFLOW model and estimated groundwater inflow rates to predict groundwater head or levels during mining, as shown in Figure 2.8. When these simulated heads are compared to the mine levels and the access tunnel elevations (Figure 2.8), it is clear that the heads are much higher than the level of the access tunnel. In other words, Golder's model predicts that water levels will not be low enough to mine the entire ore body. Mine inflow rates for both the base-case and upper bound exhibit this problem. This demonstrates that Golder's groundwater inflow rates to the mine are too low, and therefore, that the estimates of inflow to the WWTP and the TWIS are too low.

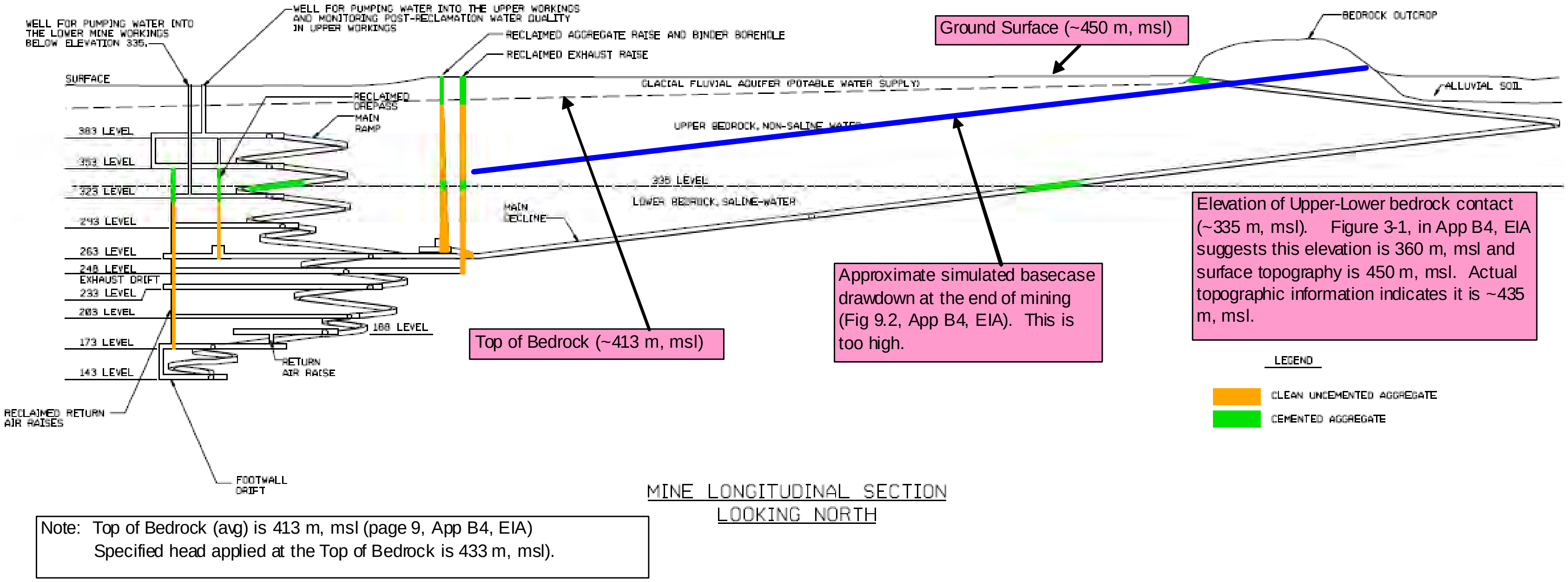


**Figure 2.8. Overlay of mine levels (left side of diagram) and the main access tunnel ("main decline") with simulated water level from drawdown.** Mine will have to be dewatered to the lowest level to access all the ore.

Source: Modified from Foth & Van Dyke, 2006b, Vol. 1, Figure 7.2.

6. *High permeability of mine workings and faults was not considered adequately by KEMC.* KEMC specified a high permeability "dilation" region surrounding the mine tunnel system that results from construction, but their model assumes that the high permeability region was not continuous from the access portal down to the mine and main ramp areas. This will bias mine inflow estimates to the low side, because it reduces potential inflow from overlying higher permeability zones along the access tunnel. In addition, KEMC only increased the permeability by a factor of 3 around tunnels (see Foth & Van Dyke, 2006b, Vol. 2, App. B-4, p. 21). This is inconsistent with findings by Sainsbury (2007) that indicate the permeability increases by several orders of magnitude as far as 400 ft from the tunnels. In addition, Golder assumed that the transmissivity values used for faults (based on testing of only one localized fracture) covers the range of possible values for all water-conductive features in the entire model area (87 $km^2$). However, the transmissivity is likely much higher along major structural features, but Golder did not investigate this possibility in the mining area.

### 2.2.2 Modifications of KEMC's models and resulting predictions

We made several modifications to the Golder FEFLOW bedrock model in order to simulate a more realistic range of possible flows into the mine due to dewatering (all modeling was conducted by Dr. Robert Prucha). The FEFLOW input and output files are included as Appendix B to this report. Six scenarios were modeled, as described in Table 2.2. A more realistic range of groundwater inflows to the mine is produced from these modifications because of the following modifications:

- Groundwater flow in the Quaternary material is included in the model. KEMC did not simulate the Quaternary aquifer explicitly. Because results from the limited pump and slug testing showed that the bedrock and the Quaternary aquifers are hydrologically connected, it makes more sense to allow the model to simulate flow in the Quaternary material.

- The faults were extended laterally to distances more consistent with those mapped by KEMC geologists (see Foth & Van Dyke, 2006b, Vol. 2, App. C-1, p. 13) and Klasner et al. (1979).

- The faults were extended into the upper bedrock aquifer rather than being confined to the lower bedrock zone. Figure 2.5 shows KEMC faults at mining level 275 m (in the upper bedrock) that also exist in the lower bedrock. Appendix C contains the Hearing Exhibit on which Figure 2.5 is based.

**Table 2.2. Scenarios modeled using FEFLOW to simulate mine inflows during operation of the Eagle Project**

| Scenario number | Original scenario description | Groundwater extraction / mine inflow (gpm) |
|---|---|---|
| 0 | Golder 2006 model with 100-foot thick overburden; dewatering boundary conditions from KEMC base case were used.[a] | 222 |
| 1 | Scenario 0 with the fracture width adjusted to 10 centimeters. | 228 |
| 2 | Scenario 1 with the tunnel impact zone extended to the overburden contact. | 229 |
| 3 | Scenario 2 with the fractures extended upward to the overburden contact. | 383 |
| 4 | Scenario 3 with the fractures extended laterally. | 364 |
| 5 | Scenario 4 with 10× fault permeability (one order of magnitude). | 3,100 |
| 6 | Scenario 4 with 100× fault permeability (two orders of magnitude). | 30,146 |

gpm = gallons per minute.

a. KEMC files used: Eagle_82_upper_casae_with_dilation_including_FRZs.dec; dewatering boundary conditions are from eagle_97_base_case_Version_01.dac. See Appendix B for FEFLOW input and output files.

KEMC only hydraulically tested one fracture zone in the single multiple-well pump test in the orebody (04EA-084). It is well known that with increasing scale of faults, permeability will also increase (Illman, 2006). Over the entire mining area and the larger model area, the fault permeability is therefore expected to increase by at least one order of magnitude. We increased the fault permeability by one and two orders of magnitude (Table 2.2). Considering that permeability can vary by 10 orders of magnitude, this is a conservative modification. Therefore, larger faults (mapped by KEMC geologists but not tested by Golder), or fault zones (i.e., mapped by Klasner et al., 1979) will show increasing permeability compared to what KEMC estimated from the 04EA-084 pump test.

KEMC predicts an upper bound mine inflow of 215 gpm (Foth & Van Dyke, 2006b, Vol. 2, App. B-4, p. 22). As shown in Table 2.2, results using modified assumptions ranged from 228 to 30,146 gpm. Correcting model inputs to connect the bedrock aquifer with the Quaternary aquifer and increase the scale and permeability of the faults by 10 times results in mine inflow rates of 3,100 gpm. Our simulations most likely still underestimate mine inflow because they did not consider the following:

- Increasing the mine inflow to actually dewater the entire portal decline and mine area (see Figure 2.8)
- The potential for crown-pillar failure or rock mass dilation and resultant increase in mine inflow
- Inflow from the Salmon Trout River directly over the mine
- Inflow from brecciated dike zones.

Our mine inflow results for Scenario 5 – 3,100 gpm – are comparable to reported mine inflows in the Marquette Iron Mining district mines, as described in the following section.

## 2.3 Inflows from Nearby Hardrock Mines

Nearby mines in the Marquette Iron Mining district had actual mine inflows that are significantly higher than those estimated by KEMC for the Eagle Project. Inflow to other hardrock mines in the area occurs mainly through faults and subsidence (Stuart et al., 1954). KEMC should have compared their inflow estimates to these nearby systems as part of their modeling exercise.

Nearby mines also show significant impacts to surface water flow. For example, at the nearby Morris Mine, mine dewatering decreased flow in the Carp River, which is about 1,000 ft away from the mine, by 400 gpm (Table 2.3). KEMC does not consider the high potential for hydraulic connection between the Salmon Trout River and the bedrock, despite the presence of the Salmon Trout River, faults, and the brecciated dike in the immediate mine area (see Figure 2.1).

**Table 2.3. Mine inflow rates, lateral extent of groundwater drawdown, and decreases in stream flow from nearby iron mines**

| Mines – Marquette Iron –Range | Maximum inflows (gpm) | Drawdown extent (ft) | Decrease in stream flow from mine dewatering |
|---|---|---|---|
| Maas-Negaunee mines | 3,000 | | |
| Mather | 4,000<br>(10 million gallons in 8 days) | | |
| Athens | 600 | | Partridge Creek (150 gpm) |
| Morris | 2,000 | 10,000 | Carp River (400 gpm) |
| Rogers Mine (Iron River) | 4,000 gpm (wells) | | Iron River (1,080 gpm/mile) |
| Source: Stuart et al., 1954. | | | |

## 2.4 Water Quality of Inflow to the Waste Water Treatment Plant

The amount of contaminated water entering the WWTP is largely controlled by the amount of water flowing into the mine (mine inflow). In addition to underestimating likely mine and WWTP inflow rates, KEMC has underestimated the concentration of contaminants in mine drainage water and has, therefore, underestimated contaminant concentrations in water entering the WWTP. Information in this section is derived from KBIC/NWF reports prepared in response to the MPA (Stratus Consulting, 2007a) and the groundwater permit application (Stratus Consulting, 2007b). These reports are summarized herein.

### 2.3.1 Potential of sulfide mines to create water quality problems

The Eagle deposit is similar in terms of geologic setting and mineralogic composition to other magmatic ultramafic sulfide deposits in the United States and elsewhere, including the Duluth deposit in Minnesota, the Stillwater Mine in Montana, the Sudbury deposit in Canada, and the Noril'sk Mine in Russia (Foose et al., 1995). The Eagle deposit is more similar to the Duluth and the Noril'sk deposits, with 50 to 100% sulfide or 32 to 38% sulfur. Mining and weathering of such high-sulfur magmatic ultramafic sulfide deposits can produce waters with elevated concentrations of nickel, copper, zinc, and other metals and neutral to low pH values. Eagle Project leach tests have reached lower pH values than the Duluth deposit leach tests. Over the course of 50-week humidity cell tests for the Eagle Project, the lowest pH reached in the metamorphosed sedimentary rock ("country rock") samples was 3.67 (1.39% sulfur), and the pH in the massive sulfide unit (MSU) sample (36.1% sulfur) at 70 weeks was 3.88. Like the Sudbury Mine in Canada (Nickel Rim, nickel-copper tailings impoundment), high nickel concentrations were reached in leach tests from the Eagle deposit. Nickel concentrations of up to 120 mg/L were reached in leachate from Eagle's semi-massive sulfide unit (SMSU) (pH = 4.56), and concentrations as high as 427 mg/L nickel (pH = 3.62) were reached in leachate from the massive sulfide ore. These values are over 1,000 times higher than health-based water quality standards for nickel. Like other similar mined deposits around the world, water quality characteristics from leached Eagle ore, host, and country rock show that high metal concentrations and low pH values are likely to result from mining of the Eagle deposit.

The ore and the peridotite, which comprise the vast majority of the managed material at the Eagle Project, clearly have a moderate (peridotite) to high (ore) ability to produce acid and contaminants and a low ability to neutralize the acid produced. The sedimentary rocks also have a high ability to produce acid and leach metals, with somewhat more ability to neutralize the acid produced. However, low pH values were reached in country rock kinetic tests with higher sulfide percentages, most likely because of the presence of pyrite. The high percentages of sulfides, including acid-producing pyrrhotite that weathers rapidly, will cause the production of acid and metals early, especially in the MSU. The type of neutralizing material present in the rocks is unlikely to counteract the acid produced over long periods of time. Because ore will be left in the crown pillar, and likely in the wall rock of the underground mine, poor water quality could be produced rapidly and last for long periods of time.

### 2.3.2 KEMC's geochemical testing

KEMC's acid-base accounting (ABA) tests did not adequately characterize all rock that will be present in the mine vicinity. The quantity and distribution of rocks and geochemical test units selected for geochemical kinetic testing are not representative of the quantity and distribution of rocks in the underground mine and waste rock. Specifically, the rock category "peridotite" can contain up to 30% sulfide (~ 10% sulfur), and samples used for geochemical testing (kinetic testing) contained a high of only 2.4% sulfur. Because leachate quality is highly dependent on the amount and type of sulfide present, using results from kinetic samples with low sulfide content could grossly underestimate acidity and sulfate and metal concentrations in leachate from mined materials.

Moreover, the reults of the kinetic tests that KEMC did conduct underestimated the contaminant leaching potential of mined material in the Eagle deposit. Results from geochemical kinetic tests underestimate long-term leachate concentrations of copper, cobalt, nickel, and sulfate because concentrations of these contaminants were still increasing at the end of the test periods, as shown in Figure 2.9. Therefore, the concentrations presented in the MPA (Foth & Van Dyke, 2006b) for the underground mine and development rock stockpile are likely lower than what may actually exist if these areas are mined.

In addition, the number of samples that KEMC tested is much lower than that recommended by generally accepted testing criteria. Mineralogy, rather than geology, should guide "rock type" and geochemical test units. More heterogeneous materials (e.g., waste rock) should have more samples than more homogenous materials (e.g., tailings). For ABA tests, Price and Errington (1994; Table 2.4) suggest that at least 26 samples should be tested for < 1 million metric tons of material, and 80 samples should be tested for 10 million metric tons of material. KEMC conducted ABA tests on only 11 samples of ore. Using 4.05 million metric tons of ore, at least double that number of ABA tests should have been conducted on the ore.

KEMC states in its MPA (Foth & Van Dyke, 2006b, Table 4-1) that 675,925 metric tons of development rock are projected to be removed from the underground mine; however, the total amount of development rock in the ground is much larger and has not been estimated. KEMC conducted ABA testing on 58 samples of intrusive rocks (mostly peridotite) and 41 samples of meta-sedimentary rocks (summarized in Eary, 2006). As shown in Table 2.5, even though more ABA testing should have been conducted, the results for all rock types show that the vast majority of the materials is expected to be acid generating.

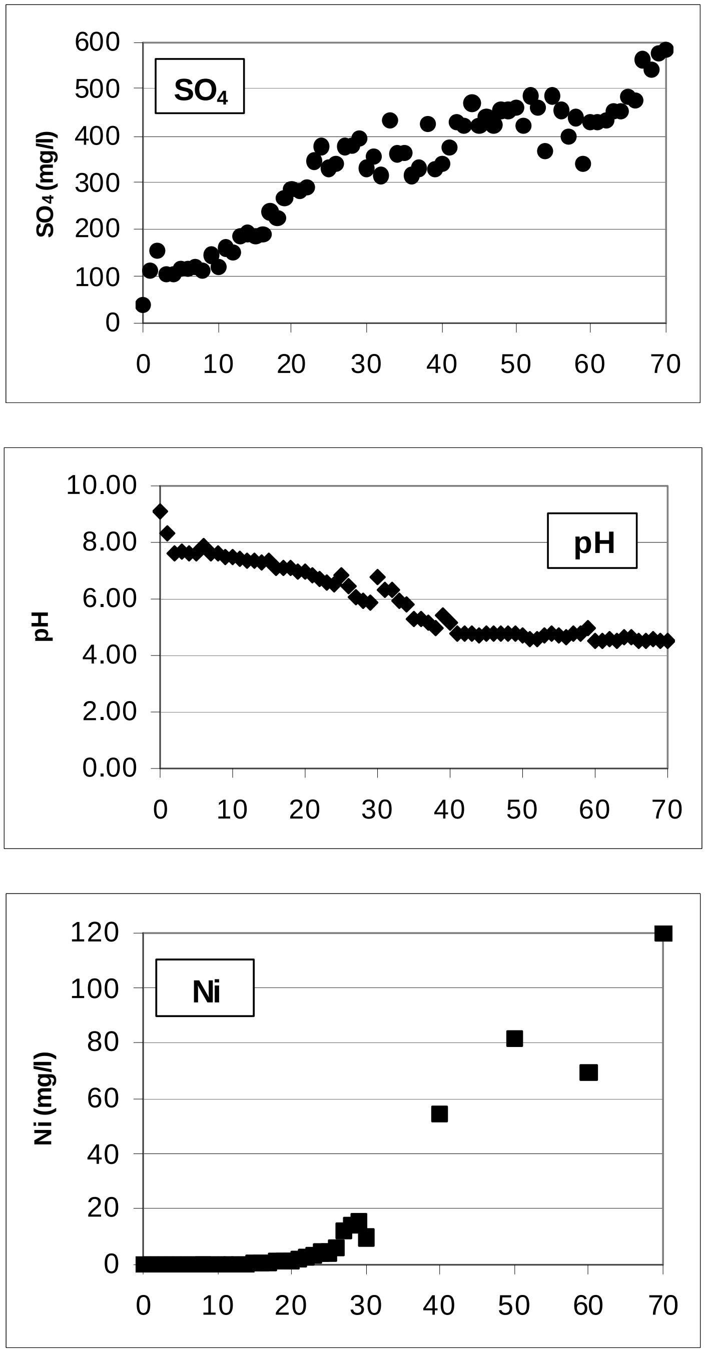


**Figure 2.9. Sulfate, pH, and nickel values over 70 weeks (x axes) in humidity cell test leachate from SMSU sample (Phase I column 4, 12.85% sulfur).**

**Table 2.4. Recommended minimum number of samples for geochemical testing from Price and Errington (1994)**

| Mass of each separate rock type (tons) | Minimum number of samples |
|---|---|
| < 10,000 | 3 |
| < 100,000 | 8 |
| < 1,000,000 | 26 |
| 10,000,000 | 80 |

More importantly, KEMC conducted only five long-term kinetic tests on intrusive rocks and seven tests on meta-sedimentary rocks. More long-term leach/kinetic tests should have been conducted on materials planned to be part of the development rock and the walls of the underground workings (access tunnels). As shown in Table 2.5, the sulfur contents of the peridotite samples used for kinetic testing did not cover the high end of the expected range. According to Kennecott Exploration (2005), the peridotite is actually referred to as disseminated ore, and it has a sulfide content of 3 to 30% (equals a sulfur content of up to ~ 10% sulfur). The peridotite samples used for kinetic testing only had up to 2.44% sulfur. Because sulfur content is one of the main controls on leaching of metals and acidity in mined materials (generally, the higher the sulfur content, the leachate will be more acidic and have higher metal concentrations), the kinetic testing results for peridotite will underestimate the possible concentrations of heavy metals and acid leached from development rock and the underground workings. Therefore, the high end of sulfate and metal concentrations from peridotite kinetic tests should be used to conservatively predict mine water quality for peridotite.

### 2.3.3 KEMC's predicted mine drainage water quality

KEMC made predictions about water quality in development rock drainage, in underground mine drainage during mining, and in water reporting as inflow to the WWTP. In all cases, KEMC underestimated concentrations of contaminants in these mine drainage waters.

KEMC's prediction of contaminant concentrations in mine drainage from the temporary development rock storage area (TDRSA) is underestimated because they neglected small size fractions in the development rock that will leach higher concentrations of metals, and they did not account for a realistic amount of ore being present in the development rock. The results in Table 2.6 show that sulfate, TDS, and all metal/metalloid concentrations are higher when smaller size fractions and more highly mineralized material are accounted for in the development rock. Because the modifications are a better reflection of conditions expected in the waste rock pile, we believe that substantially higher concentrations of contaminants are likely in the development of rock stockpile leachate. These higher concentrations will affect water quality flowing into the underground mine, entering the WWTP, and being discharged to groundwater at the TWIS.

**Table 2.5. Percent sulfur or sulfide, acid generation potential, number of kinetic tests run per rock type, and %S of samples used for kinetic testing of the Eagle deposit**

| Rock type/geochemical unit | %S or sulfide in unit | Summary of acid generation potential[a] | Number of kinetic tests run | %S of samples for kinetic tests |
|---|---|---|---|---|
| Sedimentary units (sandstone/siltstone/ hornfels) | 0.2-1.4%S | 69% AG; 11% uncertain; 20% non-AG | Siltstone: 5<br>Sandstone: 1<br>Hornfels: 1 | 0.31 to 2.1%S |
| Peridotite/disseminated sulfide unit/ pyroxenite (along margins of the intrusions, above and below the upper sulfide zone and above the lower sulfide zone) | 3-15% sulfide (disseminated sulfide)<br>Disseminated sulfide = < 30% sulfide | 61% AG; 16% uncertain; 23% non-AG | Peridotite: 4<br>Pyroxenite: 1 | Peridotite: 0.2 and 2.44%S<br>Pyroxenite: 0.99%S |
| Massive sulfide unit | > 80% sulfide<br>50-100% sulfide<br>32-38%S | 3/3 Phase I samples AG | 1 | 36.1%S |
| Semi-massive sulfide unit | 30-50% sulfide<br>12-15%S | 3/3 Phase I samples AG | 2 | 12.9 and 8.13%S |

a. Using 3:1 NP:AP and Sobek method.

AG = acid-generating; S = sulfur.
%S in most common sulfides (e.g., pyrrhotite, pentlandite, chalcopyrite) ranges from 33 to 42%.

Sources: Geochimica, 2004 (for sulfur percentages); Kennecott Exploration, 2005 (for sulfide percentages).

**Table 2.6. Comparison of development rock stockpile water quality using different inputs and assumptions – before modeling to include limestone**. All units in mg/L unless noted.

| | Geochimica (2005) | 90% 10 cm, 10% 1 cm; 5% SMSU |
|---|---|---|
| Sulfate | 575 | 5,940 |
| Nickel | 8.33 | 102 |
| pH (SU) | 6.60 | NC |
| TDS | 956 | 8,340 |
| Aluminum | 3.46 | 79.8 |
| Arsenic | 0.08 | 0.018 |
| Beryllium | 0.0019 | 0.051 |
| Cadmium | 0.0002 | 0.185 |
| Calcium | 79.3 | 804 |
| Cobalt | 0.0008 | 4.14 |
| Copper | 5.58 | 184 |
| Iron | 26.8 | 383 |
| Lead | 0.0004 | 2.17 |
| Magnesium | 88.3 | 496 |
| Manganese | 2.50 | 6.95 |
| Selenium | 0.0037 | 0.30 |
| Zinc | 1.90 | 17.7 |

NC = not calculated.

KEMC failed to include an analysis of the thicker crown pillar and resulting changes in mine water quality in the Groundwater discharge Permit Application (GDPA; Foth & Van Dyke, 2006a). In the MPA, mining was proposed to progress to the 353-m level [~ 85 m below ground surface (bgs)], with selective mining at the 383-m level (~ 55 m bgs), leaving a much smaller crown pillar with essentially no ore. However, Sainsbury (2007) recommends that mining be limited to below the 327.5-m level, resulting in a thicker crown pillar (87.5 m). That recommendation was adopted as a condition of the MDEQ's proposed mining permit (see Special Permit Conditions No. E5), but the GDPA was not revised to account for that change.

With the thicker crown pillar, ore from the MSU and SMSU would remain in the crown pillar after mining. Water moving through this rock would leach metals and sulfate and create acidic drainage waters in the underground mine during operation. This point was ignored in calculations of mine water quality in the GDPA, and by doing so the GDPA will further underestimate the concentrations in mine drainage water and water reporting to the WWTP.

Using maps of rock types at different depths in the mine area, we estimated the percentage of peridotite, metasedimentary rocks, MSU, and SMSU at three different elevations in what will become the crown pillar; and used 3% MSU, 37% SMSU, and 50% peridotite as percentages of ore and intrusives remaining in the crown pillar. We also added a small amount of metasedimentary rock (10%, subtracting from SMSU and peridotite) to account for the presence of this rock type. Estimates of water quality draining from the crown pillar during mining used kinetic testing leachate concentrations for this mix of rocks. The resulting concentrations of metals are substantially higher than background water quality in the bedrock or glacial aquifers, which is what KEMC assumes for the quality of all mine inflow.

KEMC's prediction of water quality in the underground mine during mining was underestimated, and correction of their mistakes produces dramatically higher contaminant concentrations. KEMC's assessment of mine leachate quality is not representative of conditions expected in the underground mine during or after options. KEMC ignored the presence of development rock in the underground mine and the presence of a larger and more mineralized crown pillar, and underestimated surface area and mine drainage concentrations, including concentrations of nitrate in the underground mine during operations. These errors mean that KEMC has very likely underestimated the concentrations of metals that will be present in the mine drainage, and therefore in the WWTP inflow during and after mine operation.

We conducted our own model predictions of mine water quality that use the same approach and spreadsheet model as Geochimica (2005), but used more realistic assumptions and conditions for six important components of the calculation that affect the mine drainage quality. Those six components, which are described in detail in the sections that follow, are:

1. Presence of development rock (as backfill) in the underground mine
2. Presence of larger and more mineralized crown pillar
3. Surface area and rock type percentages for mine workings and development rock
4. Humidity cell leachate concentrations
5. Amount of groundwater infiltration
6. Concentrations of nitrate in mine drainage.

Comparison of our and KEMC's modeled WWTP inputs (see Table 2.7) shows that predicted concentrations of many metals, including aluminum, barium, beryllium, cadmium, calcium, cobalt, copper, iron, lead, magnesium, manganese, mercury, nickel, and zinc, are substantially higher in our analysis. The higher values are largely the result of the higher predicted concentrations in mine drainage.

**Table 2.7. Composite mine drainage composition for selected constituents for the expected amount of groundwater inflow during years 4 and 7 of operation, and comparison to KEMC values**

| **Source** | | **Stratus Consulting (2007a)** | | **KEMC** |
|---|---|---|---|---|
| **Year of operation** | | **Year 4** | **Year 7** | **Not specified** |
| **Groundwater inflow** | | **75 gpm** | **75 gpm** | **180 gpm** |
| **Parameter** | **Units** | | | |
| TDS | mg/L | 1,128 | 832 | – |
| Aluminum | mg/L | 3.29 | 4.93 | 0.156 |
| Antimony | mg/L | 0.005 | 0.005 | 0.021 |
| Arsenic | mg/L | 0.013 | 0.010 | 0.027 |
| Beryllium | mg/L | 0.010 | 0.005 | 0.001 |
| Boron | mg/L | 3.58 | 3.56 | 4.04 |
| Cadmium | mg/L | 0.028 | 0.016 | 0.013 |
| Calcium | mg/L | 65.2 | 80.9 | 47.0 |
| Cobalt | mg/L | 2.67 | 0.733 | 0.73 |
| Copper | mg/L | 7.67 | 11.3 | 0.155 |
| Iron | mg/L | 99.7 | 34.0 | 7.25 |
| Lead | mg/L | 0.104 | 0.135 | 0.01 |
| Manganese | mg/L | 3.14 | 1.02 | 0.992 |
| Nickel | mg/L | 132 | 36.8 | 36.4 |
| Ammonia | mg/L as nitrogen | 0.111 | 0.111 | 10.2 |
| Nitrate + Nitrite | mg/L as nitrogen | 90.6 | 90.6 | 0.05 |
| Silica | mg/L $SiO_2$ | 6.09 | 8.51 | – |
| Sulfate | mg/L | 636 | 473 | 118 |
| Thallium | mg/L | 0.002 | 0.001 | 0.008 |
| Zinc | mg/L | 0.992 | 1.13 | 0.165 |

Source: Foth & Van Dyke and Associates, 2006a, Table 4-2.

## 2.4 Summary

The major hydrogeologic issue regarding inflow to the TWIS is that the estimates of mine inflow are too low by several factors to an order of magnitude. This is a critical factor in the overall design of the TWIS, because the largest component of flow at the TWIS derives from inflow to the proposed underground mine. When more realistic assumptions are used as modifications to the Golder FEFLOW model, much higher inflow estimates are predicted. The more realistic higher inflows are supported by actual inflow rates for similar underground mines in the area.

In addition to underestimating likely mine and WWTP inflow rates, KEMC has underestimated the concentration of contaminants in mine drainage water, and has, therefore, underestimated contaminant concentrations in water entering the WWTP. Comparison of our and KEMC's modeled WWTP inputs shows that predicted concentrations of many metals, including aluminum, barium, beryllium, cadmium, calcium, cobalt, copper, iron, lead, magnesium, manganese, mercury, nickel, and zinc, are substantially higher in our analysis. The higher values are largely the result of the higher predicted concentrations in drainage coming into the underground mine. Therefore, KEMC's predictions of water quality entering the WWTP are very likely underestimated.

# 3. Waste Water Treatment Plant Issues

The WWTP is designed to accept water from the underground mine (largest percentage of inflow to the WWTP), main operation area stormwater runoff, truck wash area, crusher, the TDRSA, and rainfall/snowmelt (Foth & Van Dyke, 2006a, Figure 4-2). The wastewater is proposed to be treated using a combination of lime precipitation, reverse osmosis (RO), and possibly ion exchange and released at the TWIS. The success of the treatment plant will determine the effluent concentrations and therefore the potential impact on USDW downgradient of the TWIS. As discussed in Chapter 2, we expect contaminant concentrations and inflow volumes to the WWTP to be greater than predicted, and both these issues present major unresolved challenges for the WWTP. More detail on WWTP issues can be found in Stratus Consulting (2007b) and testimony from Dr. Glenn Miller (Appendix D), and the GDPA (Foth & Van Dyke, 2006a).

## 3.1 The Water Entering the WWTP Will Be Challenging to Treat

Wastewater from sulfide mining, and the Eagle Project in particular, poses significant treatment challenges. The composite water from the mine (which derives from many sources) is unusual and possibly unique because it includes acid mine drainage, saline water, and the presence of boron, which is notoriously difficult to remove. Individually these types of wastewaters are treated relatively successfully, but the treatment of a combination of such wastewaters is untested and remarkably complicated. The fact that the WWTP contains so many components is an indication of how difficult it will be for KEMC to treat the wastewater generated by the mine to acceptable levels.

The influent water to the treatment system almost certainly will have a relatively high variability. Pretreatment is critical for RO success, and a highly variable water quality (particularly with respect to metals) can affect the water treatment success, and subsequently the quality of the discharge water. For example, if the TDRSA receives a large amount of water, the acidity and metals load, as well as the quantity of water, can result in a higher concentration of contaminants that may well adversely affect the membranes in the RO systems. Regular monitoring and reporting of influent water quality should be, but is not, required by the MDEQ Permit (MDEQ, 2007). Only influent flow monitoring is required under MDEQ's permit. The only waste characterization requirement is narrative ("The chemical, biological, and physical quality of the influent wastewater shall not be altered such that the treatment system will no longer produce an effluent that is in compliance with the limitations described in Part I, Section 2 of this permit;" MDEQ, 2007, p. 14).

## 3.2 The Treatment System Is Highly Complex, Poorly Described, and Untested

The most common type of treatment for acid mine drainage is lime precipitation, and the most common type of treatment for saline waters is RO. Because of the unique combination of contaminants, both types of treatment are proposed for the Eagle Project WWTP. While other RO systems have worked for mine drainage, this system is one of the only ones that will be required to work 24 hours a day, 7 days a week (with interruptions limited to only the retention volume in the contact water basins (see Dr. Glenn Miller testimony, Appendix D).

The WWTP system involves the following major steps and chemical additions (Foth & Van Dyke, 2006a, Figure 6-1):

1. Metals precipitation (add lime and polymer)
2. Clarifier (sludge settles)
3. Gravity filtration (add sulfuric acid before and after)
4. First pass RO (add biocide, antiscalant, and cleaning chemicals before); concentrate goes to concentrate reduction process (CRP)
5. Second pass RO (add caustic and cleaning chemicals before); concentrate goes to CRP
6. Treatment notes say that in lieu of caustic addition, an ion exchange system for boron may be added before the second pass RO step
7. Final pH adjustment.

The design of the treatment is overly complex, and is an untested and unconventional system in the industry. Untested systems are usually fraught with start-up problems and do not initially perform to meet expectations, which would inevitably result in discharges that will contaminate the USDW into which the WWTP effluent discharges. In addition, KEMC has never submitted a treatability or pilot test to demonstrate the effectiveness of its novel, complex WWTP system, and crucial aspects of the treatment system process are still not finalized. For example, KEMC has not decided on the approach for removing boron (see item #6 above). One of the limiting or critical factors with the overall treatment system is its ability to remove boron. KEMC's boron removal efficiency estimate is overly optimistic, and even under that optimistic view, the expected effluent boron concentration (174 µg/L) is close to the MDEQ permit limit (285 µg/L).

In the GDPA (Foth & Van Dyke, 2006a), the first step in the treatment process is described as either lime softening or lime precipitation. Lime softening and lime precipitation generally have different goals. Lime softening is designed to remove calcium from the wastewater, while lime precipitation is designed to also remove other divalent metals such as lead and cadmium, which are present in acid mine drainage and generally requires a greater amount of lime (calcium hydroxide). If the water quality is poorer than predicted and variable, the addition of lime will be more complicated and probably will result in damage to the membranes. This is one of the more cumbersome aspects of the treatment system, and the variability of influent water quality will be difficult to compensate for and may, therefore, have a negative effect on the treatment.

The coagulation polymer, anti-scalants, and the biocide were not specified in either the MDEQ Permit (MDEQ, 2007) or the UIC Application (Foth Infrastructure and Environment, 2007), which is based on information prepared for MDEQ for the GDPA (Foth & Van Dyke, 2006a). Because at least a portion of the biocide will be discharged into the groundwater, the risk of this discharge must be evaluated. The efficiency of removal of the biocide used in the RO treatment has not been examined by KEMC.

The largest fouling problems will likely be encountered in the CRP. This is the stage of the treatment process that has the highest load of contaminants and that will generate an important part of the sludge that will require disposal. No details are presented regarding the CRP or disposal of the sludge from the lime precipitation unit or the RO units.

There are no actual data on treatment of Eagle Project wastewater, only theoretical predictions. The predictions are based on existing data that most likely used RO new membranes and water that did not resemble the combination of acid drainage and brine that will be generated by the Eagle Project.

## 3.3 The Treatment System Is Not Designed to Accommodate the Likely Increased Influent Volume

As discussed in Chapter 2, we expect that the influent volume for the WWTP easily will be one order of magnitude higher than predicted by KEMC. The two primary RO systems are each designed for 175 gpm, and KEMC claims that only one of these systems will be sufficient to treat the volume of wastewater expected. However, as explained in Chapter 2, KEMC's predictions of WWTP inflow volumes are not correct, the WWTP may not be able to "rest" one of the two RO systems for any significant amount of time because of the high inflow volume.

The predicated wastewater inflow rate is one of the most significant deficiencies in the design of the treatment system. If the inflow volume is higher than KEMC predicts for the WWTP (350 gpm), the system will fail because it will easily be beyond its design capacity. The only solution would be to increase the size of the treatment system or discharge untreated or only partially treated wastewater. Increasing the size of the WWTP will require a major redesign effort and will require a major increase in the capacity of the TWIS and storage basin facilities on the Site.

While the TWIS is designed for 400 gpm, KEMC's design requires that one of the five TWIS discharge cells be rested at any given time (Foth & Van Dyke, 2006a). Thus, under typical TWIS operating conditions, the maximum volume of water that can be injected over the long-term is 320 gpm, which is even less than the volume of water that the WWTP is designed to treat (350 gpm). Clearly, if there is a much larger volume of water coming into the WWTP, the proposed treatment and injection system will fail.

## 3.4 Treatment Will Not Be Able to Meet Permit Limits Protective of USDW If Influent Quality Is Worse than Expected

As discussed in Chapter 2, the WWTP influent water quality likely will be substantially more contaminated than predicted, which will have an impact on the first stages of the water treatment system (first RO system), as well as the CRP. Larger amounts of sludge will be produced in the lime precipitation unit, and larger amounts of salts will be produced in the crystallization/evaporation system.

Applying the same removal efficiencies predicted in the MDEQ GDPA (Foth & Van Dyke, 2006a, App. G1 and G2) to the higher influent concentrations predicted by Stratus Consulting (2007b), a number of contaminants will exceed federal and state drinking water standards (Table 3.1) and would therefore not be protective of the USDW. Under these conditions, expected effluent concentrations of aluminum, arsenic, cobalt, copper, lead, and nitrate would exceed federal and state standards, goals, and advisories for the protection of drinking water. If substantially higher inflow concentrations occur, as predicted by Stratus Consulting (2007b), the WWTP would need to be redesigned, and different removal rates would apply. KEMC has not addressed the likelihood of having to treat higher WWTP inflow concentrations – either in the design of the treatment and sludge disposal systems or its storage facilities. The combination of higher inflow volumes and concentrations would result in exceedences of standards in groundwater and contamination of the USDW.

**Table 3.1. Expected effluent concentrations using higher predicted WWTP inflow values from Stratus Consulting (2007a) and comparison to federal and Michigan water quality standards, goals, and advisories**

| Parameter | Units | Stratus influent concentration[a] | Removal rate[b] (%) | Stratus Consulting expected effluent concentration | MCL[c] | SMCL | MCLG | Lifetime health advisory[d] (mg/L) | Part 22 std in (mg/L) | Part 201 std (mg/L) | Effluent exceeds standard, goal, or advisory? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | mg/L | 6.12 | 98.70 | **0.081** | – | 0.05 to 0.2 | – | – | 0.150 | 0.050 | **Yes: SMCL, Part 201** |
| Arsenic | mg/L | 0.012 | 95.00 | **0.002** | 0.01 | – | 0 | – | 0.005 | 0.010 | **Yes: MCLG** |
| Beryllium | mg/L | 0.011 | 95.00 | 0.001 | 0.004 | – | 0.004 | – | 0.002 | 0.004 | No |
| Boron | mg/L | 3.4 | 99.30 | 0.161 | – | – | – | 1.0 | 0.250 | 0.500 | No |
| Cadmium | mg/L | 0.033 | 94.70 | 0.002 | 0.005 | – | 0.005 | 0.005 | 0.0025 | 0.005 | No |
| Cobalt | mg/L | 2.62 | 98.60 | **0.037** | – | – | – | – | 0.02 | 0.04 | **Yes: Part 22** |
| Copper | mg/L | 14.2 | 95.00 | **0.707** | 1.3 (TT) | 1.0 | – | – | 0.500 | 1.0 | **Yes: Part 22** |
| Iron | mg/L | 107 | 99.95 | 0.053 | – | 0.3 | – | – | 0.300 | 0.300 | No |
| Lead | mg/L | 0.18 | 94.60 | **0.010** | 0.015 (TT) | – | 0 | – | 0.002 | 0.004 | **Yes: MCLG, Part 22, Part 201** |
| Manganese | mg/L | 3.14 | 99.70 | 0.009 | – | 0.05 | – | 0.3 | 0.05 | 0.050 | No |
| Nickel | mg/L | 126 | 99.99 | 0.018 | – | – | – | 0.1 | 0.05 | 0.100 | No |
| Nitrate + nitrite | mg/L as N | 88.1 | 33.10 | **59.0** | 10 | – | 10 | – | 5 | 10 | **Yes: MCL, MCLG, Part 22, Part 201** |
| Sulfate | mg/L | 762 | 99.00 | 7.68 | – | 250 | – | – | 250 | 250 | No |
| Thallium | mg/L | 0.002 | 94.40 | 0.0001 | 0.002 | – | 0.0005 | 0.0005 | 0.001 | 0.002 | No |
| Zinc | mg/L | 1.6 | 95.00 | 0.080 | – | 5.0 | – | 2.0 | 1.2 | 2.4 | No |

a. Stratus Consulting, 2007a, Year 4 of mine operation.
b. Foth & Van Dyke, 2006a, Appendix G: after second pass RO.
c. MCL = maximum contaminant level; SMCL = secondary maximum contaminant level; MCLG: maximum contaminant level goal; TT = treatment technique. See U.S. EPA, 2007.
d. U.S. EPA, 2006.

Part 22 Standards: Foth & Van Dyke, 2006a, Appendix G1. Part 22 standard for arsenic was changed to 0.005 mg/L to reflect the new lower Part 201 standard of 0.010 mg/L. Part 201: Residential Drinking Water Criteria, Table 1 R 299.5744.

## 3.5 KEMC's Contingency and Quality Assurance Measures Are Inadequate

KEMC does not have a contingency plan for treatment of higher than expected volumes of water or water with substantially higher contaminant concentrations. The main storage contingency for higher WWTP inflows (beyond the contact water basins) is diversion to the TDRSA (Foth & Van Dyke, 2006a). If water needs to be diverted to the waste rock facility, the acid generated in this system will require additional treatment to allow for passage through the RO system. The additional lime precipitation required will generate additional sludge, and the disposal of sludge has not been adequately addressed by KEMC. In addition, KEMC does not have a clear plan for quality assurance of the treatment process.

There is apparently no plan for how the precipitated sludge or the evaporation/crystallization residue will be managed. These residues are different chemically and pose different levels of risk. KEMC has simply stated that they will be managed "according to current regulations" (Foth & Van Dyke, 2006a). On the order of 10 to 20 tons/day of sludge and hydrated salts from the crystallization/evaporation systems will be generated and require disposal. The salts and sludge will contain boron, heavy metals, biocide, and other contaminants.

Neither the MDEQ nor KEMC have a clear plan for quality assurance of the treatment process, and this is a critical deficiency. Although there are suggestions that one will be developed, there is really no set of criteria for when the following will be decided:

- When will the membranes be cleaned or replaced? What are the criteria for making such decisions?
- When is the system out of control? What are the constituent concentrations that will indicate the system is no longer functioning and requires maintenance? What are the administrative procedures to make this decision? What are the record keeping requirements for this procedure?
- How will the quality assurance data be reported to the MDEQ and EPA?
- How will the MDEQ and EPA independently monitor the operation of the water treatment system, other than to rely on the monthly and quarterly sampling required under the groundwater discharge permit?

## 3.6 Lack of Numeric Effluent Limits in the MDEQ Permit

The protection of the USDW at the Eagle Project site relies on MDEQ placing protective limits on the effluent from the WWTP. However, key contaminants that are difficult to remove have no numeric effluent limits in the MDEQ Permit (MDEQ, 2007). In fact, very few numeric limits exist in the MDEQ Permit for the WWTP effluent. The lack of control at the effluent allows downgradient contamination of one of Michigan's premier USDWs. The following constituents have no numeric effluent limits in the MDEQ Permit: ammonia, nitrate, nitrite, phosphorous, chloride, sodium, SC, aluminum, antimony, barium, beryllium, boron, chromium, cobalt, fluoride, iron, lead, manganese, molybdenum, nickel, potassium, strontium, sulfate, thallium, vanadium, and zinc. The lack of effluent limits in the MDEQ Permit means that the first line of defense for protection of groundwater is absent and that any impacts to downgradient groundwater will not be known for weeks or longer. If KEMC is certain that their effluent will meet concentrations for "expected water" in the GDPA (MDEQ, 2007, Appendix G), they should demonstrate this by meeting strict numeric limits in the effluent at the WWTP.

# 4. Hydrogeologic and Geochemical Issues Downgradient of the TWIS

In this chapter, we discuss the hydrogeologic and geochemical issues related to the TWIS area. The sections in the chapter cover the following areas: hydrogeologic characterization (4.1); the direction of groundwater flow before and after TWIS discharge (4.2); the conceptual model of groundwater flow (4.3); KEMC modeling of TWIS discharge and groundwater flow (4.4); alternative modeling of TWIS discharge (4.5); the adequacy of the TWIS monitoring system (4.6); and the protectiveness of MDEQ's groundwater discharge permit on groundwater (4.7) and surface water (4.8) quality.

## 4.1 KEMC Did Not Adequately or Accurately Characterize the Unsaturated and Saturated Zone beneath the TWIS

U.S. EPA's UIC Class 5 application instructions (U.S. EPA, 2005) identifies the following characterization needs for hydrogeology and movement in the subsurface[1]:

- All USDW within one-quarter mile of the facility's property boundaries. The vertical limits of the cross sections detailing the geologic structure should extend at least 50 ft below the lowermost USDW affected by injection operations
- The direction of water movement in each USDW which may be affected by injection operations at this facility
- Geologic structure of the local area (including the lithology of the injection interval)
- Generalized maps illustrating the regional geologic setting
- Description of how the fluids move though the system from generation of the wastewater to the release of the fluids into the subsurface from the injection well, including any treatment the fluids receive at any point before injection.

KEMC's characterization of the hydrogeology in the TWIS area is poor, and does not meet all of the requirements listed above. Because of the lack of important characterization information, KEMC is unable to accurately identify the geologic setting, the extent of the hydrogeologic units

1. Region 5 Underground Injection Control, Class V Permit Application Instructions, from: Instructions – Attachments / U.S. EPA Form 7520-6.

in the TWIS area, or even the direction of groundwater flow. The major hydrogeologic characterization issues for the saturated and unsaturated zone are discussed in Sections 4.1.1 and 4.1.2, respectively.

### 4.1.1 Saturated zone characterization

**Inappropriate and inadequate number of borehole and groundwater well locations**

The most significant flaw in KEMC's characterization is the lack of any boreholes or monitoring wells between the TWIS and KEMC's presumed surface water venting locations to the northeast (Figure 4.1 – yellow highlighted areas are possible venting locations) As a result, no geologic cross-sections were provided to U.S. EPA, as required for a UIC permit application, that clearly describe all saturated and unsaturated zone stratigraphy from the point of discharge at the TWIS in the direction of groundwater flow. The only cross-sections that KEMC provided (Figure 4.2) are to the southwest of the TWIS, which is in a direction exactly 180 degrees from KEMC's proposed northeast groundwater flow direction.

**KEMC failed to consider major structural and hydrogeologic basin features in the TWIS discharge/pathway area**

KEMC failed to consider the effect of major hydrogeologic basin features (e.g., dikes, faults, major surface drainage features) on groundwater flow conditions in the TWIS discharge area and in areas potentially affected by the discharge.

A number of notable geologic structural and geomorphic features are clearly evident throughout the Yellow Dog plains area, and these features likely dominate local groundwater flow conditions. KEMC has not investigated the impact of these features on hydrostratigraphy or groundwater flow.

Several large east-west trending dikes were mapped by KEMC geologists, as shown in Figure 4.3. KEMC shows a set of northwest-trending faults/shears and also a set of east-west trending mafic dikes that occur both north and south of the TWIS location just north of the East Eagle area.

Klasner et al. (1979) mapped a similar set of faults and dikes (Klasner et al., 1979, Figure 7). The Cp zone he shows on the map refers to a ~ 500-m wide fault zone, as shown in Figure 2.1. Klasner et al. (1979) mapped dikes associated with the orebody and Eagle East outcrop.

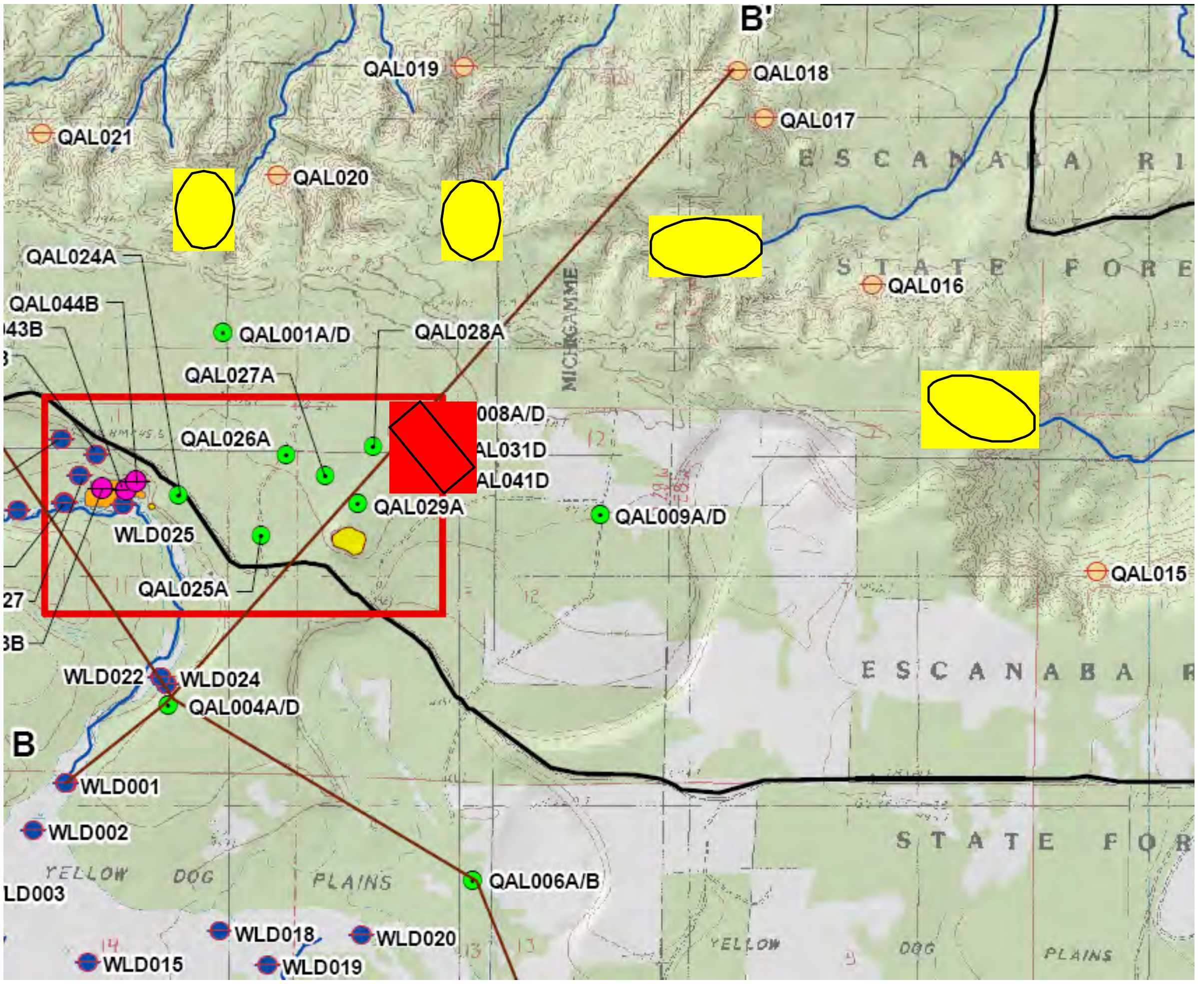


**Figure 4.1. Existing groundwater monitoring well and borehole locations in the Eagle Project area.** Note that there are no groundwater monitoring wells between the TWIS (rectangle inside solid red square) and the presumed surface water venting locations (yellow highlighted areas). Quaternary alluvium wells are labeled QAL. WLD are wetland boreholes.

Source: Modified from Foth & Van Dyke, 2006b, App. B-1, Figure 8.

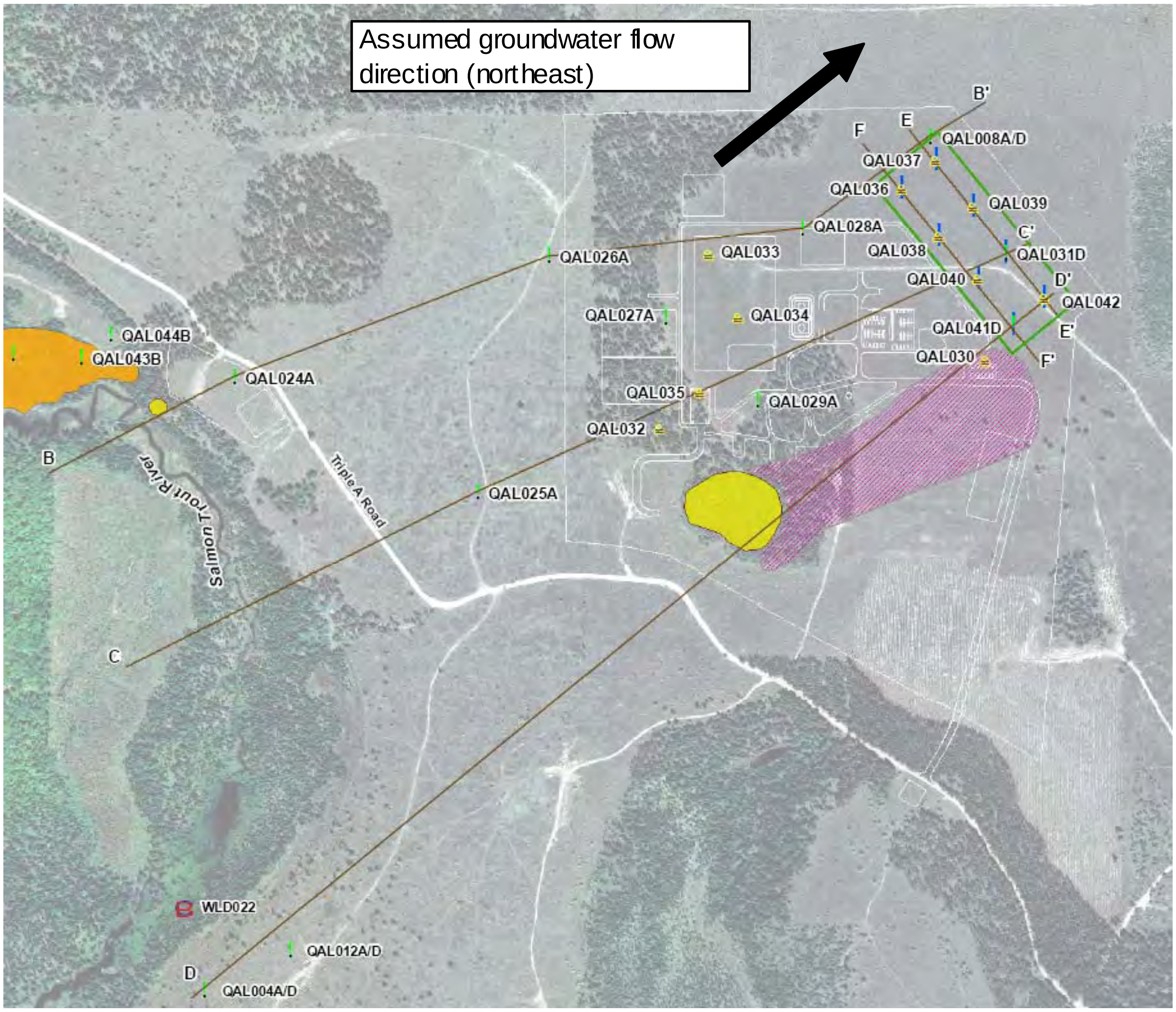


**Figure 4.2. Existing monitoring well and cross-section locations in TWIS area.** The black arrow (added) indicates KEMC's presumed direction of flow for water discharged at the TWIS. The TWIS area is shown as a green rectangle in upper right corner. Note that there are no cross-sections northeast of the TWIS in the presumed direction of groundwater flow.

Source: Modified from Foth & Van Dyke, 2006b, App. B-1, Figure 16.

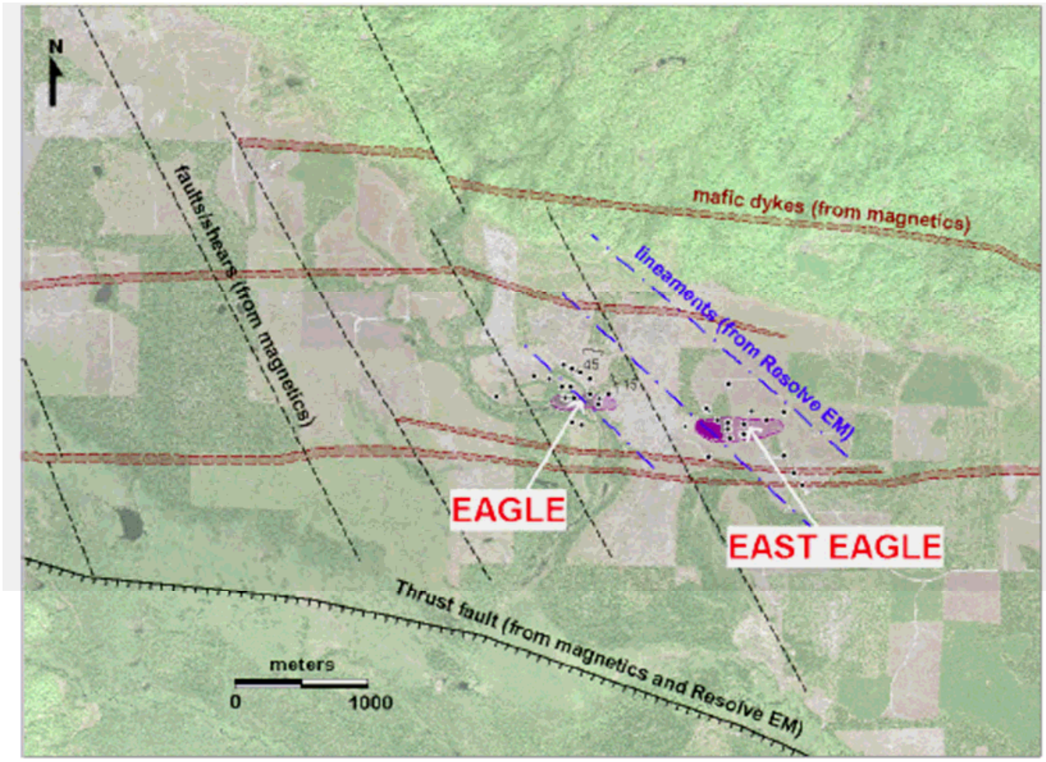


**Figure 4.3. Major structural and geomorphic features in the Eagle Project area.**

Source: Foth & Van Dyke, 2006b, App. C-1.

A third source of structural information was found on the website of Prime Meridian Resources Corporation (PMR, 2007), a mineral exploration company that has studied the Baraga Basin extensively. The Eagle Project is located in the eastern part of this basin. Prime Meridian stated:

> Structural geology has been primarily interpreted from regional magnetic surveys. Northwest striking features cross-cut and horizontally displace the general west-northwest strike of the metasedimentary stratigraphy. These are cut and horizontally displaced by younger northeast-striking structures. The northeast faults also displace the Yellow Dog dike and are therefore late or post-Keweenawan in age.

It is clear from this statement that an additional set of northeast-striking faults extends through the proposed mining area, yet this was never described in KEMC documentation. A detailed geologic map of the Baraga basin is also provided on this website (PMR, Undated) and points out the Eagle deposit. This map shows east-west trending dike traces that extend south and north of the TWIS/Eagle Project area and continue for many miles beyond what KEMC showed on its fault/dike figure. These structures and features can affect groundwater movement in the Eagle Project area, yet they were not adequately considered by KEMC in its UIC analysis.

To better coordinate the available structural information in the TWIS discharge area, we synthesized it in a geographical information system (GIS) (Figure 4.4). This figure shows the traces of large structural features (i.e., faults, dikes, fault zones, and topography) relative to the TWIS. Several points can be made about the mapping of structural faults/dikes:

- The KEMC geologists map longer northwest trending faults (red) than those mapped by Klasner et al. (1979) (orange), though Klasner actually maps a fault zone that extends through the Eagle East outcrop and the orebody (black line). KEMC never investigated the potential for these faults to control groundwater flow.

- There is a clear lack of characterization of geology in the fault zone area due to the lack of boreholes/wells (green dots).

- A dike (shown as a light blue line) runs right beneath the TWIS area (Klasner et al., 1979). However, KEMC did not acknowledge this or attempt to study its possible effect on groundwater flow.

- Klasner et al. (1979) map faults (orange) along dikes (light blue), yet KEMC did not investigate the very likely occurrence of preferential groundwater flow within brecciated zones along the edges of dikes (particularly those north of the TWIS). Intrusion of these dikes likely caused elevated bedrock areas. Flow across dikes is typically very low, due to the low permeability of these features, so it is very likely that groundwater flowing north/northeast from the TWIS would be realigned similar to the dike orientation (to the east).

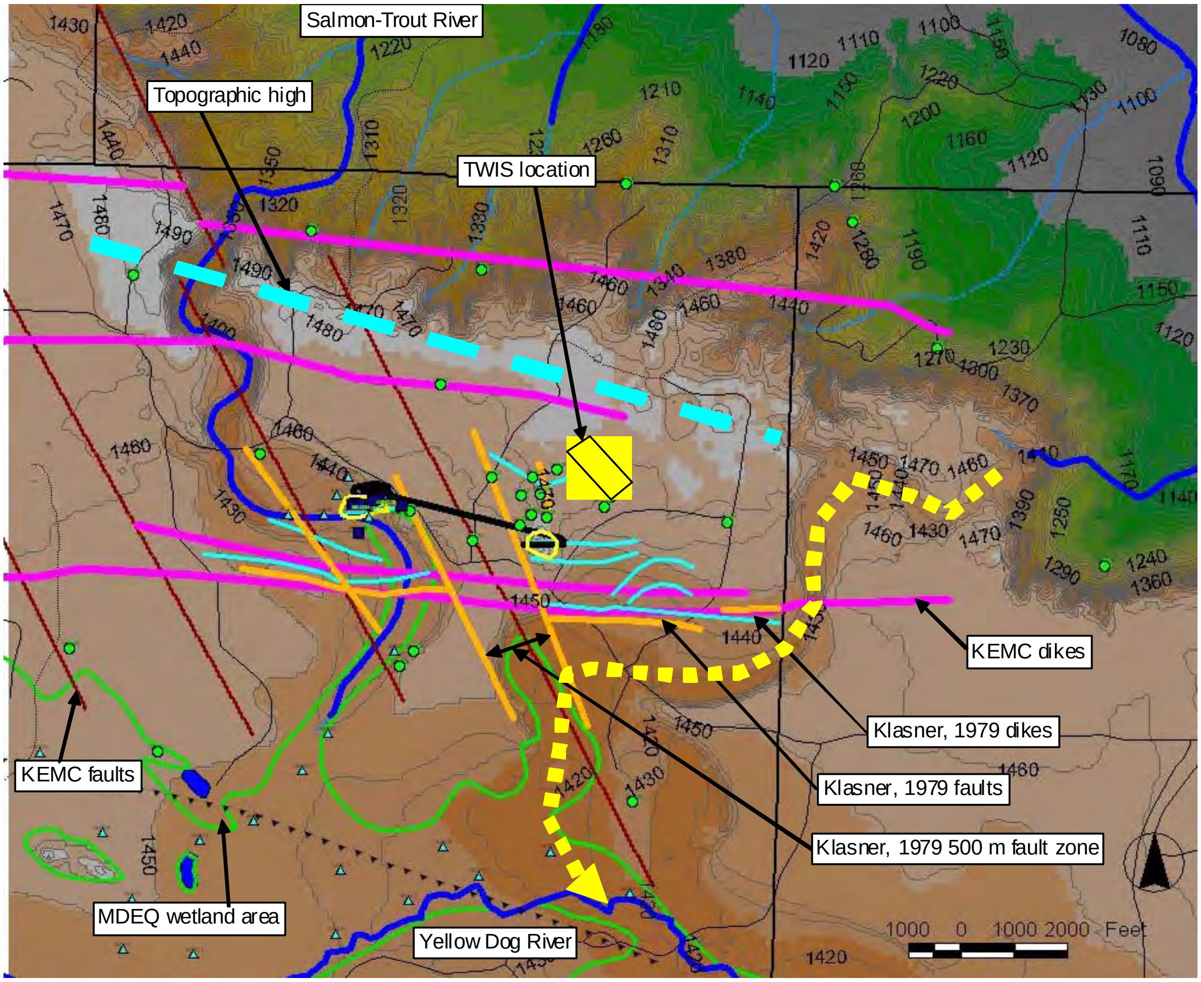


**Figure 4.4. Major hydrogeologic features in the vicinity of the TWIS.** Features are labeled. Green dots are wells, light blue triangles are wetland piezometers. The black line in the center is the approximate location of the mine tunnel. The yellow areas at either end of the tunnel are the ore bodies. The thick dashed light blue line is a fault and the approximate boundary between the Yellow Dog Plains and the Negaunee Moraine to the north. The shaded map underlying the features is the surface topography. Associated topographic contours are labeled in feet, msl. The large dashed yellow arrow just east and south of the TWIS is a major surface drainage feature draining into the Yellow Dog River to the south.

Additional points can be made about the relationship between structural features and topography or surface drainage:

- KEMC's geologists (Foth & Van Dyke, 2006b, App. C-1, p. 12) state:

  > Joint patterns often align with stream patterns suggesting they have exerted some control over drainage development.

  Clearly, even KEMC's own geologists believe that a strong correlation exists between the occurrence of surface streams and bedrock structural features. Similar findings were stated in hydrogeologic study conducted in nearby Marquette Iron Mining District (Stuart et al., 1954):

  > Faulting, and shear zones developed by the intrusion of the diabasic rocks are important factors controlling drainage lines in areas where few or no other pronounced rock structures exist.

  Despite these typical correlations observed in fractured/faulted environments, KEMC failed to investigate these relationships in critical areas and instead appears to have adopted a simplified conceptualization prior to characterizing the system.

- The ground surface elevation north of the TWIS increases and then rapidly decreases into the northern-sloping terrace of Yellow Dog Plains, referred to as the Negaunee Moraine (coarse textured glacial till of extremely heterogeneous particle size; see Foth & Van Dyke, 2006b, App. B-1, p. 9). The relationship between these features and groundwater flow was never investigated by KEMC. The topography along the northern edge of the Yellow Dog Plains is elevated along an east-west trending line that generally coincides with a regionally extensive (miles) east-west trending dike mapped by KEMC. The dike likely impedes groundwater flow to the north/northeast and causes groundwater flow to align with the dike and flow to the east. No boreholes or wells were ever constructed in this area to investigate this regional structural feature. This is surprising, given the extent to which KEMC mapped springs in the area north of the TWIS.

- A major surface drainage feature immediately east and south of the TWIS drains into wetlands (green lines in Figure 4.4) south of the TWIS and eventually into the Yellow Dog River. Although this feature starts at the northern edge of the Yellow Dog Plains, it does not drain immediately north into the Negaunee Moraine area, but instead drains south and westward. This is nearly opposite to the direction KEMC presumes for natural groundwater flow from the TWIS. This feature is more pronounced (i.e., broader and deeper) than the Salmon-Trout River, and nearby wells demonstrate that the feature acts as a local drainage feature for the underlying shallow aquifer system. This major surface feature makes several abrupt 90-degree changes in direction as it makes its way to the Yellow Dog River directly south of the TWIS. The abrupt changes seem related to the occurrence of subsurface structures in the area (dikes and faults) that show remarkably similar alignment (see Figure 4.4). In fact, the last south-trending extension of this drainage feature, which drains as a wetland into Yellow Dog River (green line), aligns well with the Klasner et al. (1979) 500-m wide fault zone that extends north-northwest between the Eagle outcrop and the orebody, or right through the proposed main access decline. This feature and its possible influence on the groundwater flow system in the area were never investigated by KEMC, yet the underlying associated structures would clearly dominate local groundwater levels and flows.

The isopach (i.e., thickness) map of Quaternary deposit (Figure 4.5) shows thickness dramatically increasing in the TWIS area. KEMC stated that the thickness of the Quaternary deposit generally increases towards the northeast (Foth & Van Dyke, 2006b, App. B-8, p. 27). However, it is clear from Figure 4.5 that the thickness instead increases dramatically to the east. This trend strongly suggests that groundwater flow directions are oriented in a similar direction to increasing Quaternary deposit thickness, rather than the presumed northeast direction. Such a change in groundwater flow direction would significantly change KEMC's predicted surface water venting locations and the impacted USDW area. U.S. EPA should require greater investigation of the hydrogeology of the TWIS area because of the large uncertainty in groundwater flow direction.

Other issues related to the Quaternary deposit thickness include:

- KEMC stated that the thickness increases "in all directions away from the peridotite outcrops, with the greatest thickness observed east and west of the Project area." This is inconsistent with their statements about Quaternary deposit thickness increasing to the northeast and suggests that KEMC is confused about basic geologic issues at the Site.

- KEMC prepared plots of Quaternary isopach thickness, which require wells drilled to bedrock, using control points like well QAL032 (Foth & Van Dyke, 2006a, App. B, p. 142). However, the log for this well does not show that bedrock was ever encountered in the borehole.

- KEMC shows bedrock contours extending just north-northeast of the TWIS (Foth & Van Dyke, 2006b, App. B-8, Figure 17). However, no attempt was made to investigate how far this critical structural feature extends north of the Yellow Dog Plains watershed and down into the Negaunee Moraine.

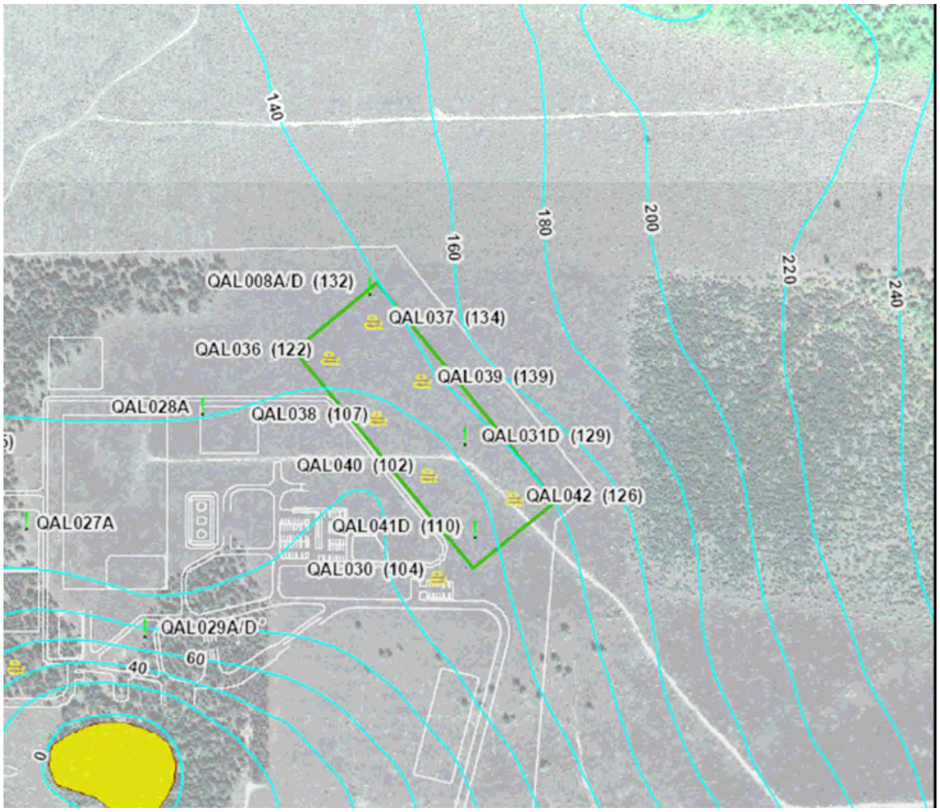


**Figure 4.5. Isopach of Quaternary deposit (ft) in the TWIS area.**

Source: Modified from Foth & Van Dyke, 2006b, App. B-8, Figure 18.

- The Yellow Dog Plain was created by glacial outwash deposits (sand and gravel). Segerstrom (1964) showed that historical glacial stream drainage was toward the southeast (toward Pinnacle Falls) and then toward the south into Mulligan Plains. The pink area on Figure 4.6 shows the glacial outwash plain. The south/southeast historical glacial drainage is consistent with the increased thickness of Quaternary deposits mapped by KEMC. It seems reasonable to assume that large-scale aquifer development and groundwater flow within Mulligan Plains may currently follow this historical drainage trend. This concept was not considered or evaluated by KEMC.

In sum, although KEMC has presented maps and cross-section of the regional geologic setting and the geologic structure of the project area, KEMC has completely failed to properly consider and interpret all the information on dikes, faults, and physical aquifer characteristics and relate it to groundwater flow conditions in the TWIS discharge area.

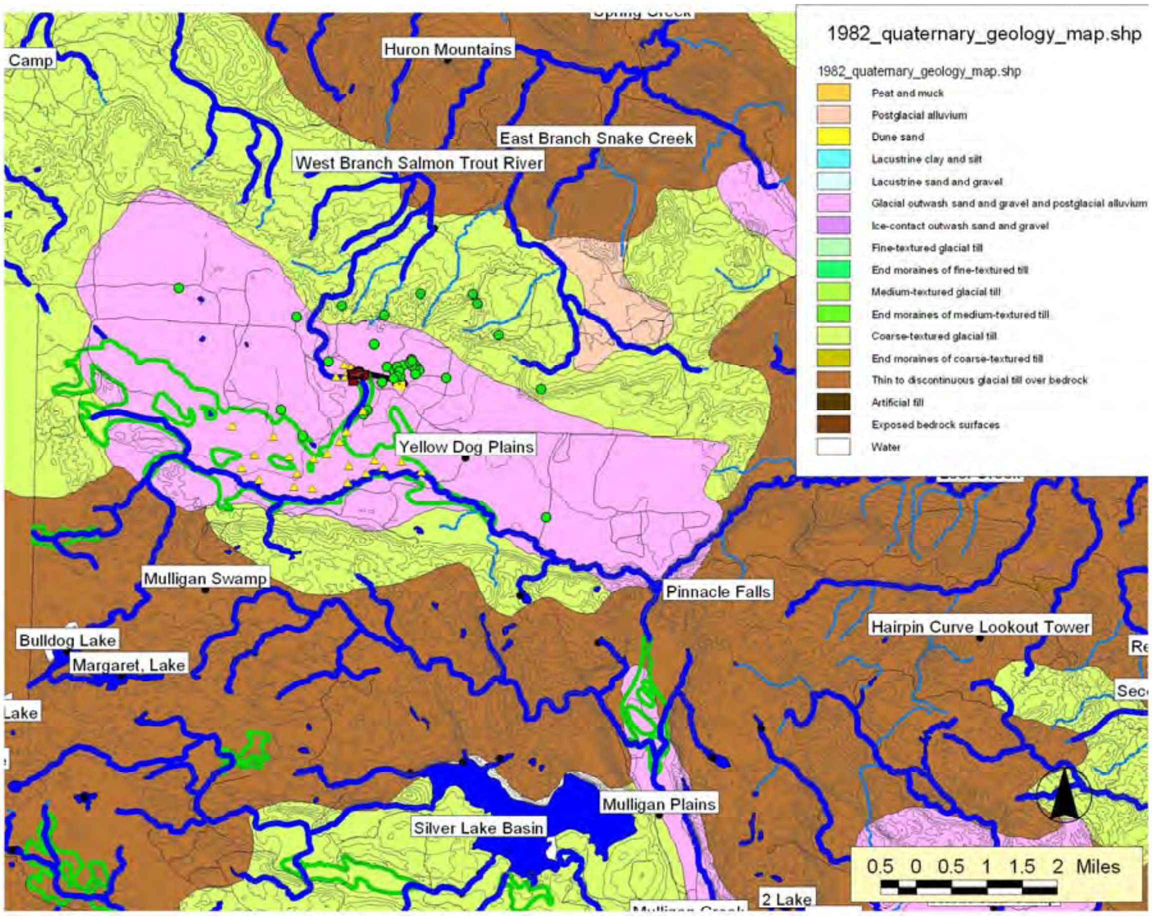


**Figure 4.6. Regional Quaternary geology in vicinity of Yellow Dog Plains.** Glacial outwash is shown in pink, coarse textured glacial till in yellow, and thin to discontinuous glacial till over bedrock in brown. Blue lines are major streams in the area (with labels shown). Green dots represent KEMC's wells; yellow triangles represent wetland piezometers. The TWIS is located immediately north of the Yellow Dog Plains label.

Source: Prepared using an ESRI Arcview GIS Shapefile obtained from the Michigan Geographic Data Library, posted by the Center for Geographic Information, Michigan Department of Information Technology (http://www.mcgi.state.mi.us/mgdl/?rel=thext&action=thmname&cid=2&cat=Quarternary+Geology). Other information was obtained directly from KEMC reports and georeferenced in GIS.

**Hydraulic testing of the saturated zone was inadequate in the TWIS area**

KEMC conducted only one multiple-well pump test to characterize the hydraulic properties of all the aquifer units [at least six units: A through E and F (Lower Outwash) in limited locations (see Foth & Van Dyke, 2006a, Vol. 2, App. B-5, Figure 11)] between the TWIS and potential downgradient locations (> 3,000 ft). Key problems with the test include:

- The test was conducted 3,000 ft from the TWIS (see Foth & Van Dyke, 2006b, App. B-8, p. 15). The test was too far away from the TWIS area to properly characterize the hydraulic properties of the TWIS aquifers.

- The stratigraphy of the test area differs dramatically from that of the TWIS. In the test area, silt and clay layers (B and C zones) are up to 90 ft thick and occur below the water table. In the TWIS area, these same units are above and below the water table, are much thinner, and are inverted in some cases (e.g., C zone lies above the B zone).

Because of these shortcomings, the methods KEMC used to characterize the hydraulic properties of the TWIS aquifer will not provide accurate information on the behavior of the TWIS discharge in the groundwater system.

KEMC conducted one "specific capacity" test in the TWIS area to characterize the hydraulic properties in one zone (D zone) of the Quaternary deposit aquifer (using well QAL031-D). These types of tests are inappropriate to use in such a complex aquifer system and will not provide reliable information on hydraulic properties. KEMC's use of the specific capacity test was additionally flawed because most of the requirements for using the method (Cooper-Jacob) were violated (see Kruseman and de Ridder, 1991), including:

- *The aquifer zone tested must be confined.* The D zone in the TWIS area is not confined, as KEMC itself reports.

- *The aquifer must be isotropic, homogeneous, and have a uniform thickness over the length influenced by the test.* Cross-sections E-E' and F-F' (also shown in Figure 4.10) clearly show that the aquifer does not have uniform thickness and is not homogenous, as indicated by the low permeability units (present in, e.g., QAL008, QAL036, QAL037, QAL038, and QAL039) that occur within the saturated zone. These low permeability units do not occur in the pumped well QAL031.

- *The potentiometric surface must be near horizontal at the start of the test.* This is anything but the case (indicated in both cross-sections E-E' and F-F' that show a strong gradient towards the southeast).

ASTM (2005) also notes that the values of transmissivity derived from specific capacity are less accurate than those determined from aquifer tests using observation wells (i.e., pump tests) because the results from specific-capacity tests represent the response of a small part of the aquifer near the well and may be greatly influenced by artificial conditions near the well, such as a gravel pack or graded material resulting from well development.

In sum, the results of KEMC's hydraulic tests of the unsaturated zone are very uncertain and not necessarily representative of hydraulic properties in the multiple aquifer zones beneath the TWIS. A number of multiple-well pump tests that tested all aquifer zones (A, B, C, D, E, and bedrock) and accounted for major structural features such as dikes and faults should have been conducted in closer proximity to the TWIS. Without this information, the behavior of the TWIS discharge (flow in the horizontal and vertical directions, effects on water table elevations, ultimate venting locations) cannot be adequately determined.

### 4.1.2 Unsaturated zone characterization

KEMC did very little to characterize the unsaturated zone (above the water table) in the TWIS area, and what was done largely ignored crucial information collected by the company. There is a relatively large unsaturated zone in the vicinity of the TWIS, and discharge from the TWIS will likely saturate large portions of this zone. However, the lack of characterization makes it impossible to know where the saturated portions will be, what direction the discharge will flow, whether or where the discharge will reach the water table, and therefore how much the discharge will be diluted or mixed with existing groundwater.

In its October 30, 2008 letter to KEMC (U.S. EPA, 2008), U.S. EPA Region 5 asked for additional information related to the nature of the "clay layer" in the immediate vicinity of the TWIS. U.S. EPA noted that the presence and extent of the clay layer would affect infiltration of the TWIS discharge. New information submitted by KEMC in response to U.S. EPA's October 30, 2008 letter is also discussed in this section.

**Cross-sections through the unsaturated zone do not accurately reflect information from borehole logs**

KEMC has wrongly characterized the unsaturated zone as a homogeneous sand. The presence of silty sand in the unsaturated zone will significantly alter the movement of TWIS discharge above the water table. Koltermann and Gorelick (1995) demonstrate that only a few percent fines can cause hydraulic conductivity values to be up to five orders of magnitude lower compared to clean sand.

Of the nine boreholes drilled in the TWIS footprint, only two (QAL008 and QAL036) show no low permeability (i.e., fines) material above the water table. The remaining seven boreholes show low permeability strata as shallow as 30 ft bgs. This is inconsistent with the statement that KEMC made in its August 21, 2008 letter to U.S. EPA (KEMC, 2008a) on p. 3:

> It is important to note that, while there is some apparent anisotropy, and a minor finer-grained layer (silty sand or clay) at depths of 60 ft or more, it is clear that infiltration behavior at the TWIS site will be dominated by the reasonably homogeneous sand for much of the depth below ground surface. This was one of the reasons the TWIS was sited in this location.

KEMC provided only two cross-sections extending northwest to southeast directly under the TWIS area (Foth & Van Dyke, 2006b, App. B-8, Figures 24 and 25). While three other sections are drawn in the TWIS area (see Figure 4.2), they extend from the TWIS to the southwest, or in the opposite direction that KEMC believes that existing groundwater and TWIS discharge will flow (i.e., to the northeast). These cross-sections are inadequate for the purposes of describing USDWs in the discharge area and do not reflect the primary information in the geologic logs.

First, KEMC should have prepared a cross-section from the TWIS discharge area through the discharge pathway to surface venting locations. Because KEMC failed to characterize the hydrogeology in potential downgradient directions, they could not provide this critical information required by U.S. EPA to perform even the most basic assessment of where the TWIS discharge will flow. Second, the information in the two cross-sections through the TWIS does not accurately reflect important information from the borehole geologic logs. Examples of issues with the cross-sections and associated boreholes are summarized below (Figures 4.7 and 4.8). Cross sections E-E' and F-F' (Figure 4.8) through the TWIS do not reflect what the borehole logs describe as low permeability units above the water table.:

- Figure 4.7 shows the geologic log for borehole QAL008. The information in the log clearly shows the presence of low permeability strata (silty sand, sandy silt) from ~ 75 to 85 ft bgs. This information is not reflected in KEMC's cross-section using borehole QAL008, shown in Figure 4.8. The purple stratum shown in the cross-section (fine sand silt and clay) should have been shown as a more continuous layer that included borehole QAL008.

- Most TWIS borehole logs (031, 037 to 042) showing silty sand at various depths above the water table were given the same graphical symbol as the sand. This is misleading because it suggests that this material is hydraulically equivalent to sand. These silty sand zones occur above the B and C zone (purple and red colored areas) shown on Figure 4.7 in areas denoted as "unsaturated sand" (brown areas).

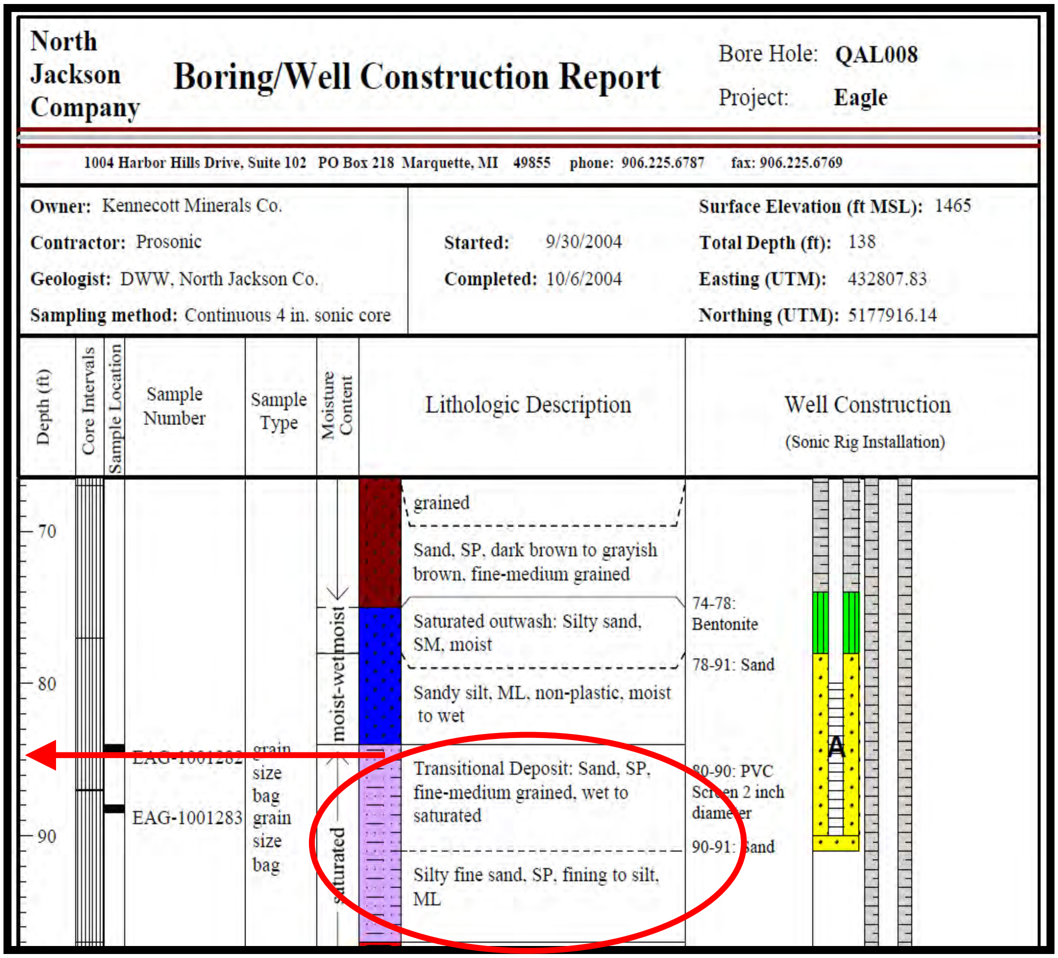


**Figure 4.7. Geologic log of borehole from well QAL008.** Red circled areas show inconsistency in elevations/depth and presence of lower permeability strata (silty sand, sandy silt) in the unsaturated zone. (Note that the Transitional Deposit starts at 1,380 ft elevation (1,465 ft surface elevation minus 85 ft); cross-section in Figure 4.8 shows transitional deposits starting ~10 ft deeper. Also, the saturated silty sand and sandy silt (blue) is shown as unsaturated sand in Figure 4.8).

Source: Modified from Foth & Van Dyke, 2006b, App. B-8, section "Geologic Logs."

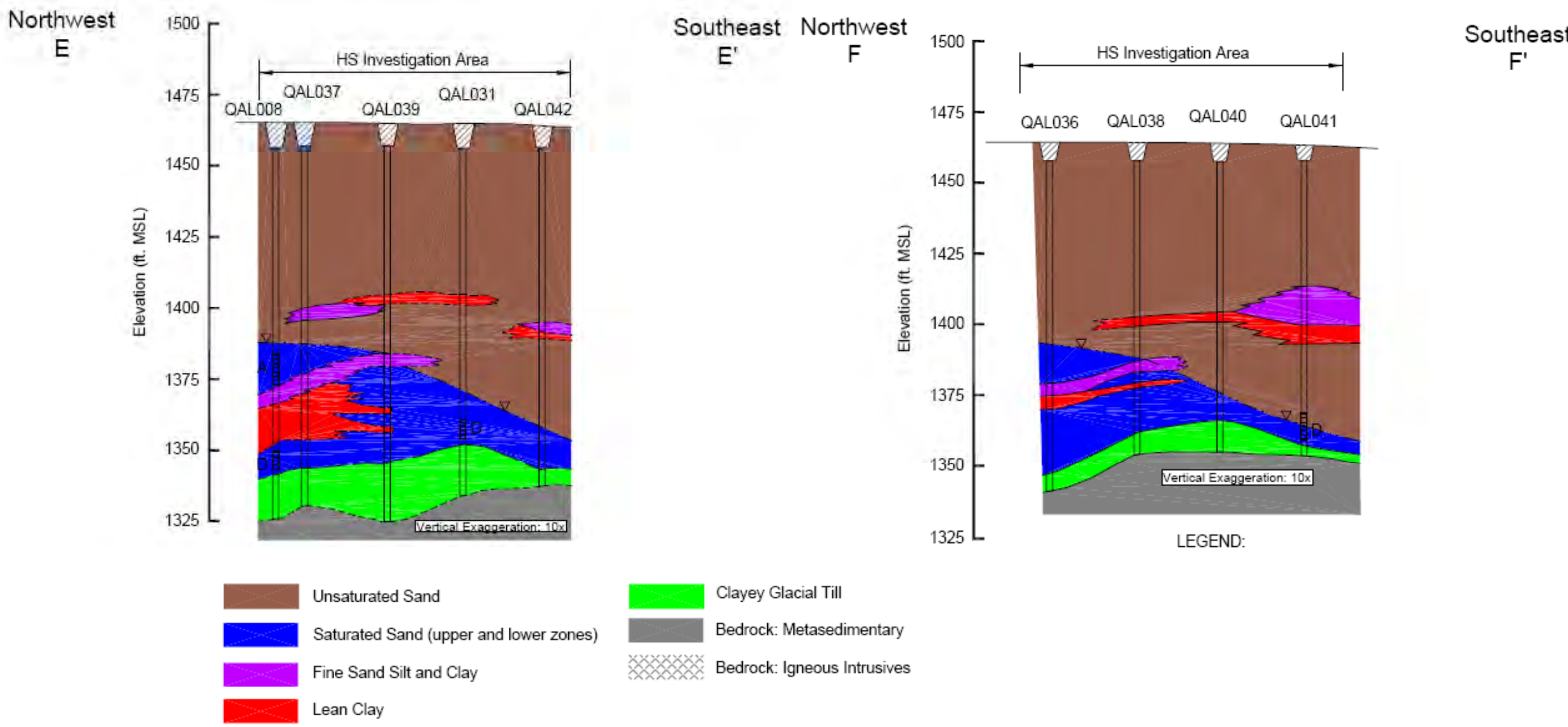


**Figure 4.8. Cross-sections E-E' and F-F' through the TWIS.**

Source: Foth & Van Dyke, 2006b, App. B-8, Figures 24 and 25.

- The log for QAL041 (immediately below the TWIS) indicates "silty sand" from 30 to 45 ft bgs, yet a USCS (Unified Soil Classification System) designation of SP-SM (poorly-sorted sand – silty sand) is specified. The designation should have been all SM. This is a significant point because the hydraulic properties can vary significantly between sand and silty sand, as noted above (Koltermann and Gorelick, 1995). Freeze and Cherry (1979) also indicate that the hydraulic conductivity of silty sand ranges over four orders of magnitude. Significant mounding can occur above silty sand, yet KEMC did not consider this in its analysis or design of monitoring wells for the TWIS.

- Borehole 031 shows "fine silty sand" at 37 ft bgs; 042 shows "silty sand" at 36 to 38 ft bgs; and 041 shows "silty sand" from 30 to 45 ft bgs. No attempt was made to correlate these shallow unsaturated zone silty sands across cross-sections E-E' and F-F' (see Figure 4.8), yet they will act as significant barriers to infiltration of TWIS discharge to the groundwater table.

- The borehole log for well 040 shows sandy silt (SM) from 68 to 80 ft bgs, yet on the cross-section F-F' no silt is shown in this zone above the water table (see Figure 4.8). Instead this zone is defined on the section as sand.

- The borehole log for 039 shows SC (clayey sand) for the USCS code, but this is inconsistent with the geologists' description of sandy clay, which has a USCS code of CL, or clay. Again, this information is shown incorrectly on cross-section E-E'. For example the SC is shown in the saturated zone and does not correlate with the lean clay (red in Figure 4.8).

- The borehole log for QAL036 (Foth & Van Dyke, 2006a, App. B, p. 150) reports a "sandy clay" below the water table (from a depth of ~ 104 to 111 ft) that they then incorrectly specify as SC and include as "saturated sand." It should have been labeled as a CL; the SC represents a clayey sand. KEMC shows only saturated sand at this depth interval on cross-section F-F' (see Figure 4.8), which implies this zone is homogenous sand. This would cause additional mounding not considered by KEMC in its analysis of discharge effects on groundwater flow.

**New information on continuity and permeability of clay layer**

In response to U.S. EPA's request for additional information (U.S. EPA, 2008), KEMC submitted new information on the continuity of the clay layer and its effect on the infiltration of TWIS discharge (KEMC, 2008c). KEMC's response suggests that the subsurface stratigraphy of the TWIS area is dominated by a thick deposit of unsaturated outwash sand with very high infiltration rates. This conclusion does not reflect information from the vast majority of the borehole logs provided (Foth & Van Dyke, 2006b, Vol. 2, App. B-8). Only two of the logs show no lower permeability layers. A substantial number of low permeability strata exist throughout the unsaturated zone well above the water table, as discussed in the previous subsection.

KEMC further suggests that low permeability "transitional deposits" (silt/sand/clay mixtures) above the saturated zone are discontinuous and will not significantly impede natural infiltration because of the absence of a perched aquifer over these units (p. 4). First, the assumption that these deposits are discontinuous is not supported by KEMC's own geologic logs (as discussed in the previous subsection). Second, the low permeability units above the water table range up to 15 ft thick. Third, although unsaturated zone modeling shows that perched conditions are not produced under natural infiltration (i.e., 13 inches (in)/year of recharge from precipitation), with the proposed discharge rate (which is > 168 times the natural infiltration rate), our modeling shows that the TWIS discharge can easily mound above these units and reach the ground surface.

On page 5 of its November 21, 2008 submittal, KEMC states that these "transitional zone deposits" are significantly more conductive than the true clay-rich lacustrine deposits, and claims that they have a hydraulic conductivity of $10^{-03}$ to 1 ft/day, compared to lacustrine deposit hydraulic conductivity of $10^{-05}$ to $10^{-02}$ ft/day. However, the hydraulic properties of the "transitional zone deposits" were not tested, so these stated hydraulic conductivity values are not supported by any data.

KEMC provided two figures that purport to show the continuity (or lack thereof) of the lower permeability layers (KEMC, 2008c, Figures 4 and 5). Neither figure shows the shallower, low permeability strata in the unsaturated zone from geologic logs (described in the previous subsection) that will cause mounding of discharge from the TWIS. The "transitional deposits" shown in the figures are at or close to the water table. KEMC states that these transitional deposits will not impede TWIS discharge, but that the lacustrine deposit present in the northwest portion of the area would cause mounding.

In sum, KEMC's submittals to U.S. EPA regarding additional information on low permeability layers in the TWIS area still do not answer U.S. EPA's main question about the continuity and permeability of these layers and their effect on infiltration rates of the TWIS discharge. KEMC should provide U.S. EPA with additional information on this topic. In the absence of this information, the results of our unsaturated zone model presented in Section 4.5 – which are based on actual information in the geologic logs and show mounding of TWIS discharge to the ground surface – represent the most likely outcome for infiltrated TWIS discharge.

## 4.2 The Direction of Groundwater Flow from the TWIS is Highly Uncertain

One of the most basic hydrologic issues about the TWIS is the direction in which the discharge will flow once it is discharged to the environment. Even this most fundamental hydraulic property has not been adequately addressed by KEMC. The paucity of wells in the TWIS area prevents the construction of any reliable groundwater contour maps under natural or discharge-related conditions. The inferred groundwater flow directions presented by KEMC are highly uncertain and do not adequately consider effects of the larger-scale basin features, as described above.

Groundwater elevation contours for the A and D Quaternary aquifer zones are presented in Figures 4.9 and 4.10, respectively. Figures 4.9a and 4.9b show KEMC's existing and more updated interpretations of groundwater flow directions in the A-zone aquifer. However, the groundwater elevations and inferred flow directions are incorrect or highly uncertain for the following reasons:

- Groundwater contours to the north of the TWIS are not supported by data because there are no wells in this area. Contour lines should be dashed to indicate that they are inferred.
- Groundwater contours for the A zone shown on Figure 4.9a are too high by more than 30 ft near springs (along streams). Note that the groundwater contours are drawn straight across deeply incised streams on the northern part of Figure 4.9. Like topographic contours, groundwater elevation contours should "point" upstream. Therefore, at the points where the blue groundwater contours cross the streams, the actual groundwater elevation is substantially lower.
- Groundwater elevations are drawn above the ground surface where they cross deeply incised streams. It is possible for groundwater heads to be higher than the ground surface if the aquifer is confined or under artesian conditions. However, KEMC has stated that the aquifer at the TWIS is unconfined (Foth & Van Dyke, 2006b, App. B-8, App. C – Aquifer Hydraulic Testing Data), so the groundwater contours should reflect actual water table elevations.

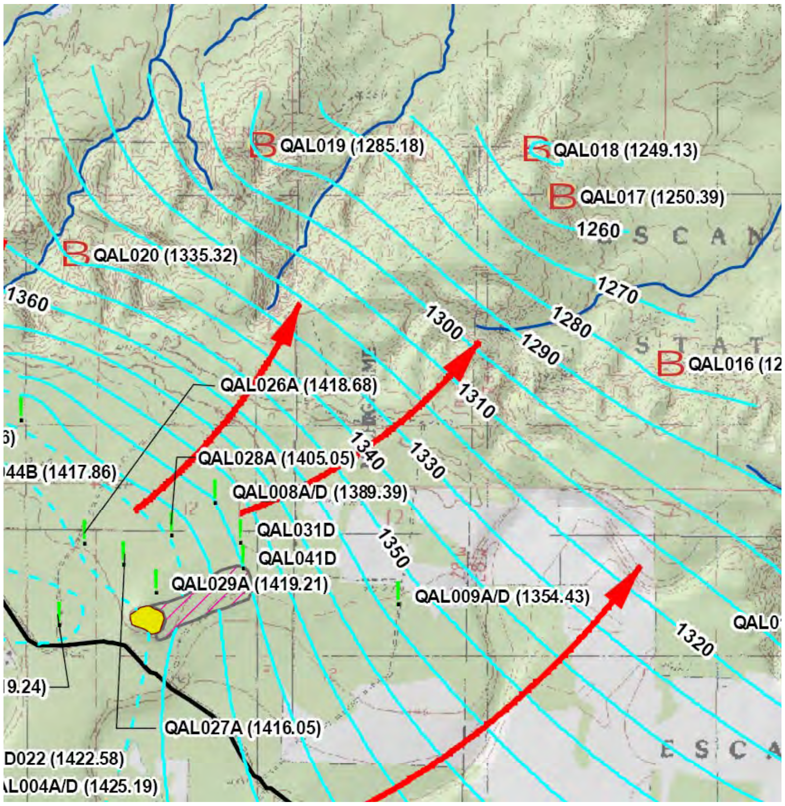


**Figure 4.9a. A-zone aquifer groundwater elevation contours.** The red arrows show KEMC's interpreted groundwater flow direction (to the northeast). Newer maps by KEMC show groundwater flow to the east/southeast, as shown in Figure 4.9b. The TWIS is located near the base of the second arrow.

Source: Modified from Foth & Van Dyke, 2006b, App. B-8, Figure 26.

- KEMC has stated that the A and D zones merge at the TWIS and the low permeability B and C zones disappear (see Foth & Van Dyke, 2006b, Vol. 2, App. B-8, Figure 20). However, the groundwater elevation contours show ~ 35 ft of head difference between the A and D zone. For example, the groundwater elevation in well QAL008A (A zone) is 1,389 ft, whereas the groundwater elevation in QAL008D (D zone) is 1,355 ft. If the two zones merge at the TWIS, there should be no difference in groundwater elevation between the two units. Moreover, the Environmental Impact Assessment shows two different groundwater elevation contour maps for the A and D aquifer downgradient of the TWIS (Foth & Van Dyke, 2006b, Vol. 2, App. B-8, Figures 27 and 28), and if the A and D zones really do merge, only one map would be necessary.

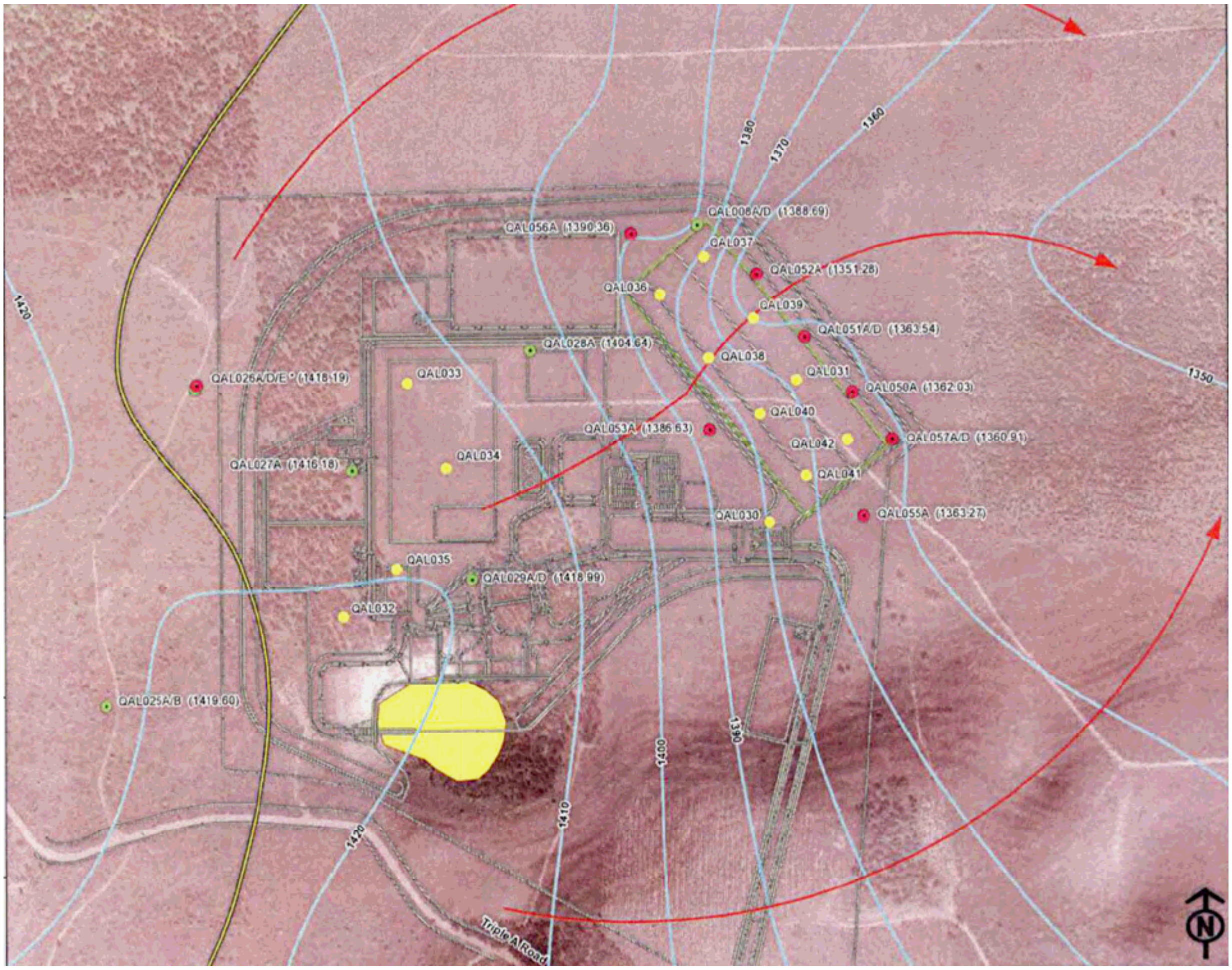

**Figure 4.9b. KEMC's updated interpretation of A-zone groundwater flow directions in the vicinity of the TWIS.**

Source: KEMC, 2008c, Figure 2.

- Groundwater elevation contours are inconsistent with gradients shown on sections E-E' and F-F' (Figure 4.10, right). Cross-sections E-E' and F-F' clearly show much larger gradients (0.034-0.037) to the southeast (shown on the cross-sections) than to the northeast (~ 0.02) (shown on the groundwater contour maps).

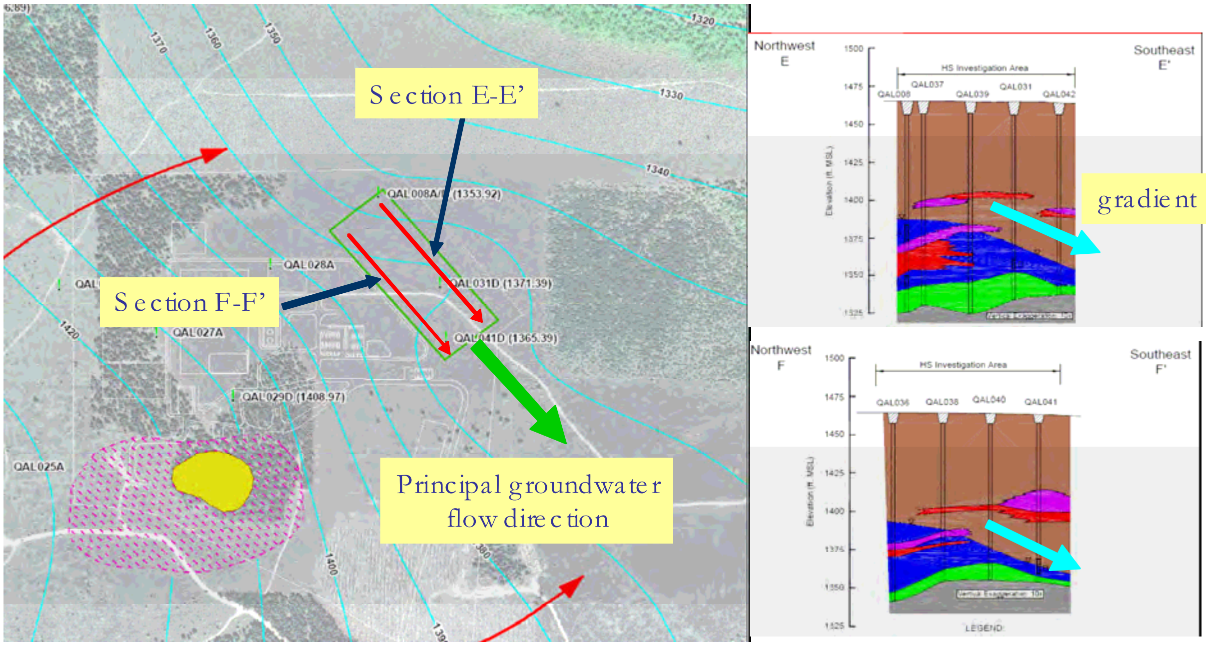


**Figure 4.10. D-zone aquifer groundwater contours (left), in light blue; annotations show the locations for cross-sections E-E' and F-F', which are shown on the right.** Red arrows are KEMC interpretations of groundwater flow directions. Blue arrows on the right figures indicate groundwater flow (following the top of saturated sand, shown in dark blue); groundwater flow in the cross-sections is to the southeast. The large green arrow on the left figure reflects the same strong SE groundwater gradient shown on the sections. Other geologic units on the cross-sections are: unsaturated sand (brown); low permeability/confining units (purple and red); glacial till (green); and bedrock (gray).

Sources: Left figure: modified from Foth & Van Dyke, 2006b, Vol. 2, App. B-8, Figure 29. Right figures: modified from Foth & Van Dyke, 2006b, App. B-8, Figures 24 and 25.

Figure 4.11 shows the same D-zone aquifer groundwater levels from Figure 4.10 and the approximate locations of dikes (from Klasner et al., 1979, shown as thicker light blue lines). Klasner et al. (1979) mapped one dike directly beneath the TWIS that is shown as ~ 2,500 ft long and oriented northwest to southeast. This dike may explain the abrupt change in groundwater levels below the TWIS (represented by the squiggle in the contour lines under the TWIS). The strong southeastern groundwater gradient shown on cross-sections E-E' and F-F' (Figure 4.10, right) is consistent with the orientation of this dike to the southeast. Higher permeability in the brecciated zone along the dike could drain groundwater from the D-zone aquifer toward the southeast and explain the drop in groundwater elevations.

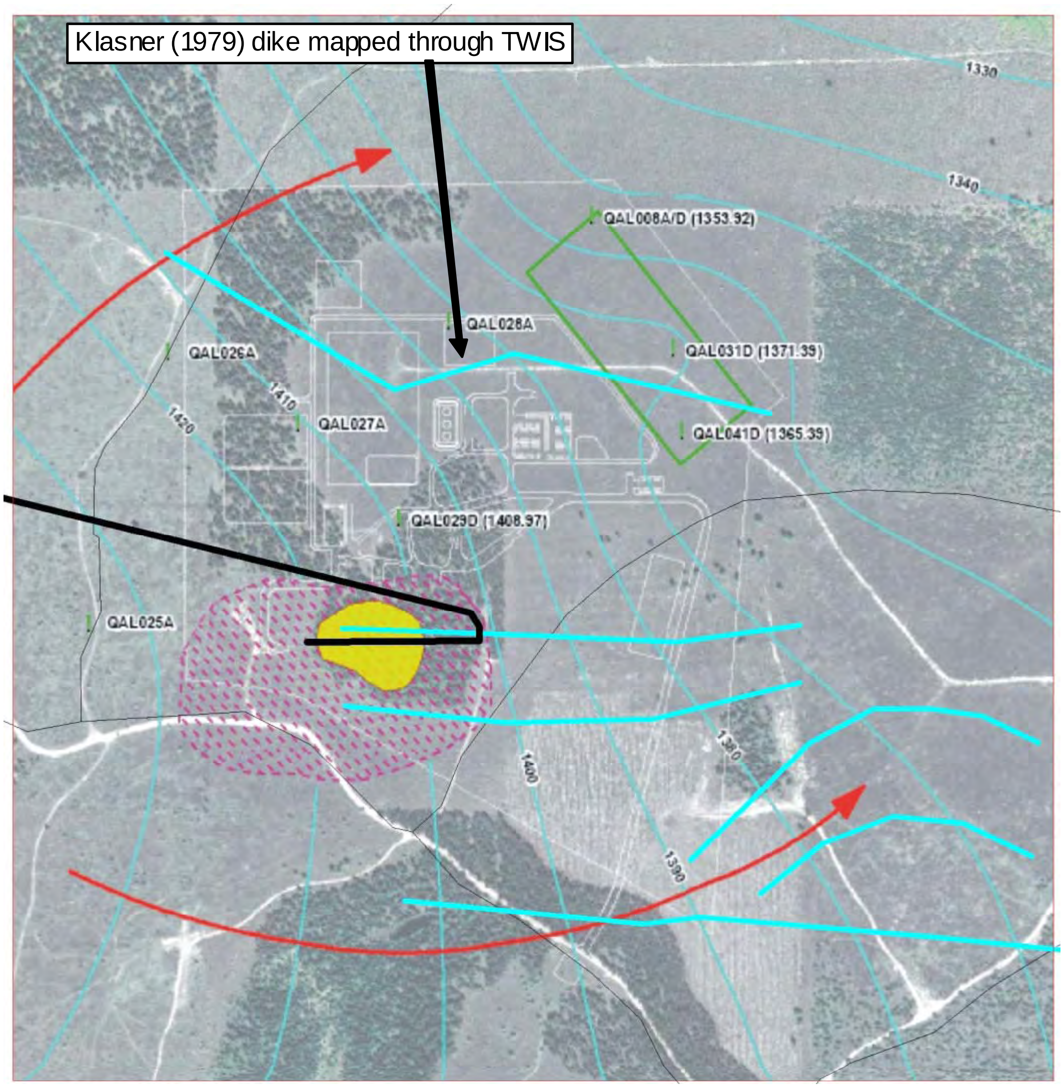


**Figure 4.11. Groundwater elevation contours for the D zone aquifer and dikes (thicker light blue lines) mapped by Klasner et al. (1979).** Red lines are KEMC's inferred groundwater flow directions in the D-zone aquifer.

Sources: Created in GIS using information from Klasner et al., 1979 and Foth & Van Dyke, 2006b, App. B-8, Figure 29.

In sum, KEMC did not develop realistic alternative conceptual flow models to explain the observed changes in aquifer thickness and structural features in the TWIS area, and instead chose a northeastern groundwater flow direction that is not supported by the available data. More realistic alternative conceptual flow models are discussed in the following section.

KEMC has consistently maintained throughout various mine permit and discharge application reports that the A and D zone aquifer groundwater flow directions from the TWIS are oriented toward the northeast. On page 4 of KEMC's November 21, 2008 submittal to U.S. EPA (KEMC, 2008c), KEMC states that regional and location potentiometric maps of the A and D zones show a very steep gradient to the northeast, which is consistent with flow in the Salmon Trout East Branch basin. However, the maps referred to in this submittal actually show an east-southeast groundwater flow direction in the A zone (see Figure 4.9b). These new figures use recently collected groundwater level information from within only 150 ft of the TWIS (see Figure 1 in their submittal for the location of new wells). No new wells were drilled by KEMC that could supply groundwater elevations (and thus gradients and groundwater flow directions) farther from the TWIS to the east-southeast or to the northeast. Groundwater flow to the east-southeast is more aligned with major structures (e.g., the east-west trending regional dike mapped by KEMC just north of the TWIS; see Figure 4.4). If these new groundwater flow directions are more accurate, more monitoring wells are needed to the east and southeast of the TWIS, and monitoring of surface water to the east and southeast of the TWIS should also be added to the monitoring program (see Section 4.6.3).

## 4.3 KEMC's Conceptual Model of Flow in the TWIS Area is Overly Simplistic and Inconsistent with Observed Data

It is standard practice in hydrogeologic investigations to develop multiple conceptual flow models (ASTM, 2002; Neuman and Wieranga, 2003). Typically, alternative conceptualizations are needed for systems with more complex flow conditions and limited data and characterization. Alternative conceptual models can be eliminated when more data are obtained, or through careful analysis using numerical flow models. KEMC made no attempt to develop realistic alternative conceptual flow models for the complicated, poorly characterized hydrogeologic flow system in the vicinity of the TWIS.

KEMC adopted an overly simplistic conceptual flow model for the TWIS area that shows flows moving to the northeast, despite inconsistencies with observed data. Figure 4.12 shows the generalized groundwater flow conceptualization proposed by KEMC.

Figure 4.13 shows an alternative conceptual flow model that is well supported by available data. The alternative model considers additional data (geomorphic, bedrock geology, structure-faults/dikes, and historical geologic development of the Yellow Dog plains aquifer system). The alternative model has the major groundwater flow direction to the east/southeast, mounding of the TWIS discharge at the surface as a result of "ponding" on lower permeability strata, and changes in aquifer thickness and groundwater flow directions in response to dikes. Flow to the east/southeast would ultimately be directed to the Yellow Dog River basin, which KEMC has not even considered.

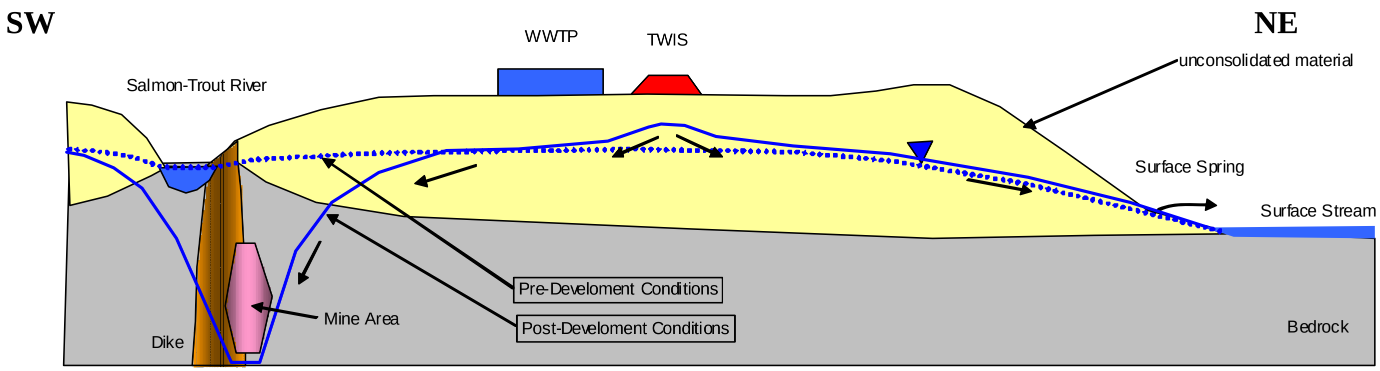


**Figure 4.12. Generalized conceptual flow model for the TWIS discharge area and downgradient area, as proposed by KEMC – looking northwest.**

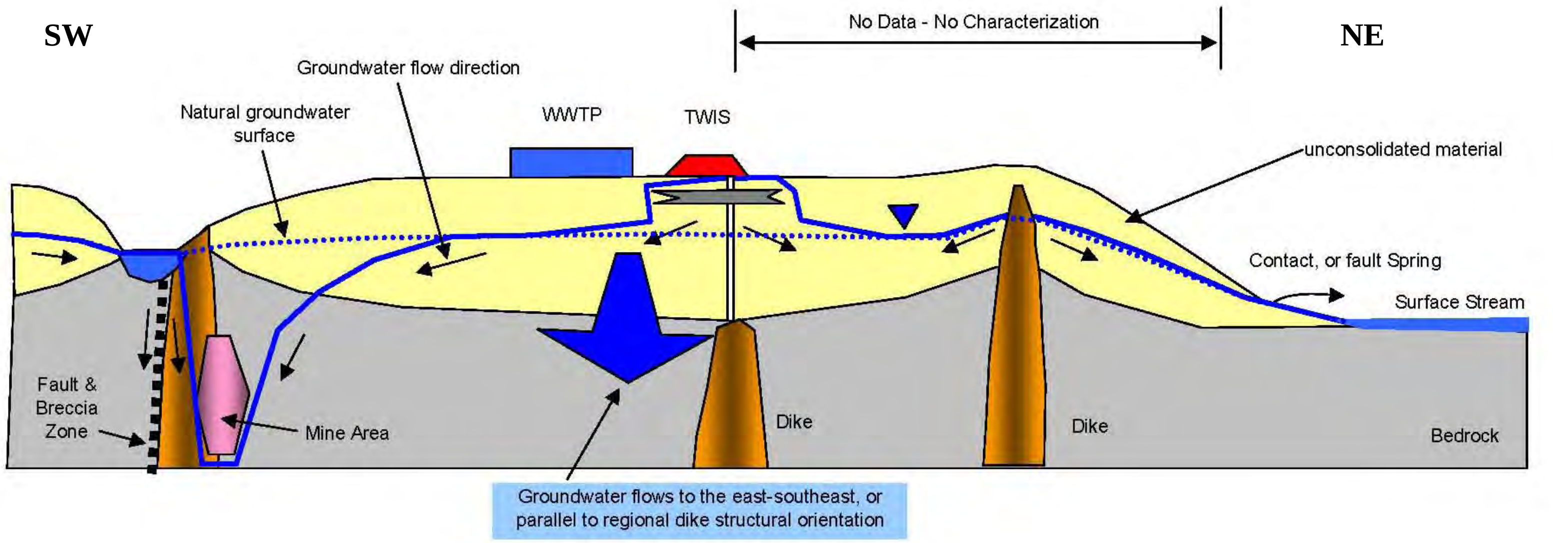


**Figure 4.13. Alternative conceptual flow model for the TWIS discharge area and downgradient area – looking northwest.** The Klasner et al. (1979) dike below the TWIS is shown in orange; gray horizontal layers under the TWIS represent low permeability strata.

In the alternative conceptual model (Figure 4.13), groundwater flow from the TWIS area is directed to the east/southeast, which is consistent with the following:

- Groundwater gradients shown on cross-sections through the TWIS
- The direction of decreasing bedrock surface elevation
- The direction of increasing thickness of Quaternary deposits
- Alignment of major dike structures both south and north of the TWIS
- Alignment of major faults in the area.

KEMC did provide several conceptual hydrogeologic or geologic cross-sections through the TWIS area, but they are inconsistent with site data (see Foth & Van Dyke, 2006b, Vol. 2, App. B-8, Figure 6 and App. B-1, Figure 6). For example, Figure 4.14 shows KEMC's suggested regional hydrogeologic profile through the Yellow Dog Plains and the Negaunee Moraine to the north. It fails to show bedrock flow, regional dikes, the peridotite dike, or major faults, all of which likely have pronounced effects on the hydrogeologic flow system. A realistic alternative is to show multiple dikes (south to north) where bedrock is elevated, thinning Quaternary deposits, and limited flow to the north. In the alternative conceptual model, flow would be directed to the east, or out of the page, draining instead eventually into the Yellow Dog River basin rather than the Salmon-Trout River basin. Given the lack of hydrogeologic information northeast of the TWIS, this conceptual model is at least as plausible as KEMC's. In fact, recent information supplied by KEMC shows that the dominant groundwater flow direction in the A zone is to the east (KEMC, 2008c).

## 4.4 KEMC's Modeling of Groundwater Discharge at the TWIS Ignores Important Hydrogeologic Information

KEMC's consultants have created four saturated-zone flow models that attempt to simulate the effects of TWIS discharge on groundwater conditions in the area. They are inconsistent with each other and ignore important hydrogeologic issues. No unsaturated zone modeling was conducted, even though the largest impacts are to what is currently the unsaturated zone. U.S. EPA has reviewed two of these models (by Fletcher-Driscoll and Golder). The third and most recent flow model was developed in 2008 by Geotrans, Inc. (Geotrans, 2008). Table 4.1 summarizes the key differences in the models. Key technical issues with all KEMC models include:

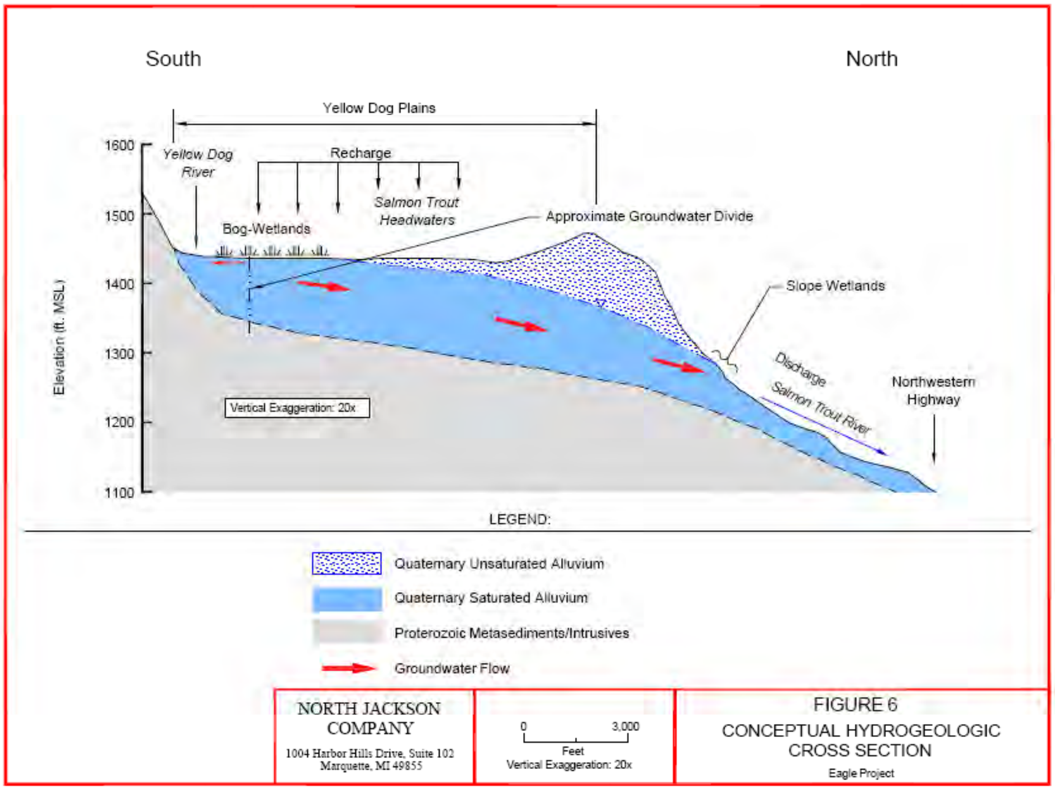


**Figure 4.14. KEMC's conceptual hydrogeologic cross section, Eagle Project, through the Yellow Dog Plains and the Negaunee Moraine to the north.**

Source: Foth & Van Dyke, 2006b, App. B-8, Figure 6.

1. It is unclear why KEMC had three different consultants prepare four significantly different flow models to simulate mounding and migration of TWIS discharge in the Quaternary aquifer. As indicated in Table 4.1, each model is considerably different, yet all are overly reliant on KEMC's (Foth & Van Dyke, 2006b, Vol. 2, App. B-5) poorly characterized and conceptualized flow system. For example, all four models failed to consider the effects of major structural features (i.e., dikes, faults, surface drainage) on groundwater flow in the TWIS area.

2. One of the most important oversights by each model is the failure to consider effects of low permeability strata in the shallow unsaturated zone beneath the TWIS. The configuration and properties of these strata will dominate groundwater mounding and groundwater direction and flow rates from the TWIS, yet none of these modeling efforts incorporated these shallow low permeability strata.

**Table 4.1. Summary of conditions and modeling details for KEMC's different groundwater flow models**

| Model # | Code | Date | Author | Current conditions predictive? | Number of scenarios | Scenarios | Model calibration | Steady state or transient | Model verification | Uncertainty analysis | Worst-case configuration? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **General model details** | | | | | | | | | | | |
| 1 | Visual Modflow | 2005 | Fletcher Driscoll | Current | 1 | Current | Yes | Steady state | None | No | N/A |
| 2 | Visual Modflow | 2006 | Fletcher Driscoll | Predictive | 2 | TWIS infiltration and dewatering | No | Transient | None | No | No |
| 3 | Modflow | 2006 | Golder | Predictive | 2 | only TWIS mounding | No | Steady state | None | No | No |
| 4 | Modflow | 2008 | Geotrans | Current and Predictive | 2 | TWIS infiltration and dewatering | Yes | Steady state | None | No | No |

| Model # | Code | Date | Author | Dewatering Q | TWIS infiltration | Model cell size | Evapo-transpiration | Recharge | Model layers | Bedrock modeled | Variable hydraulic properties |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model configuration** | | | | | | | | | | | |
| 1 | Modflow | 2005 | Fletcher Driscoll | N/A | N/A | 50 × 50 m | No | Spatially variable | 11 | Upper | Variable |
| 2 | Modflow | 2006 | Fletcher Driscoll | ~74 and ~223 gpm | 80 and 255 gpm (base and upper) | 50 × 50 m | No | Spatially variable | 13 | Upper and lower | Variable |
| 3 | Modflow | 2006 | Golder | None | 400 gpm | 100 × 100 ft | No | None | 3 | No | Uniform |
| 4 | Modflow | 2008 | Geotrans | 60 | 65 gpm | 50 × 50 m | No | Uniform | 2 | No | Mostly uniform, small low K zone over mine |

**Table 4.1. Summary of conditions and modeling details for KEMC's different groundwater flow models (cont.)**

| Model # | Code | Date | Author | Velocity calculated? | Particle tracking | Mounding at TWIS | Areal extent mounding | Maximum drawdown at mine | Areal extent drawdown at mine | Maximum baseflow change | Uncertainty Analysis | Model problems |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Model results** | | | | | | | | | | | | |
| 1 | Modflow | 2005 | Fletcher Driscoll | No | N/A | N/A | N/A | N/A | N/A | N/A | N/A | |
| 2 | Modflow | 2006 | Fletcher Driscoll | Not specifically. But 5 to 10 year travel time to vent. | Yes | 8 ft – base, 21 ft – upper bound | ~1.3 miles (~2 ft contour)-base ~1.9 miles (~2 ft contour)-upper | 0.75 ft – upper bound, 0.5 ft – base case | 30 acres – upper bound | 0 cfs (base), 0.02 cfs (upper) | None | Yes. Bedrock flux cells go dry. Wrong code! |
| 3 | Modflow | 2006 | Golder | No | Yes | 18 ft | ~2.5 miles (2 ft contour) | | | | None | |
| 4 | Modflow | 2008 | Geotrans | No | No | 15 to 18 ft | 1.5 mile around TWIS (0.5 ft contour) | 2.4 to 2.8 ft A-zone | 1.0 mile diameter, (0.5 ft contour) | < 0.05 cfs | None | |

K = hydraulic conductivity.

Sources: Fletcher Driscoll 2005 Model: App. C of App. B-5, Fletcher Driscoll 2006 Model: App. B-7; Foth & Van Dyke, 2006b, Vol. 2. Golder Associates 2006 Model: Foth & Van Dyke, 2006a, App. E-3. Geotrans 2008 Model: Geotrans, 2008.

3. Both the Fletcher-Driscoll and Geotrans predictive models rely on input from Golder's bedrock flow model (Foth & Van Dyke, 2006b, Vol. 2, App. B-4) using the FEFLOW code to simulate effects of mine dewatering on the Quaternary aquifer. A number of critical flaws in the bedrock flow model (summarized in Section 2.2) make these models inappropriate for assessing TWIS mounding and migration.

4. Neither the Fletcher-Driscoll nor the Golder model is calibrated to actual site conditions. Although Fletcher-Driscoll attempted to calibrate their multi-layer model to steady state pre-mining groundwater elevations, they subsequently significantly modified model input without re-calibrating.

5. All three predictive models rely on the U.S. Geological Survey (USGS) code MODFLOW, which does not simulate two important conditions:

   a. **Variable saturation.** A variable saturation type code is needed to assess the presence and effects of the shallow low permeability strata in the unsaturated zone.

   b. **Desaturation of confined aquifer units.** Because MODFLOW cannot simulate this condition, Fletcher-Driscoll's results for the upper bound case had noted mass-balance/dry cell problems, Geotrans did not simulate the Golder upper bound case, and Golder did not simulate mine dewatering, only TWIS mounding and migration.

6. It is unclear why Golder did not develop a single coupled bedrock-Quaternary aquifer FEFLOW model. FEFLOW can also simulate unsaturated zone conditions and density-dependent flow conditions and has the advantage of being able to simulate the explicit fractures within the bedrock. MODFLOW can't simulate flow within discrete fractures, though Fletcher-Driscoll attempts to model this zone using MODFLOW.

7. None of the models simulated localized recharge associated with the Non-Contact Water Infiltration Basins (NCWIB) (see Foth & Van Dyke, 2006b, Figure 4-2 for location near TWIS).

8. None of the predictive models included an uncertainty analysis to qualify predictions. This is both standard and essential in systems (such as the TWIS and mining area) where data, conceptualization, and parameter uncertainty are high.

## 4.5 Modeling Using More Realistic Conditions Shows that TWIS Discharge Will Reach Ground Surface

We conducted simple two-dimensional unsaturated zone flow modeling using the available information from the borehole logs and TWIS inflow values from KEMC. The modeling included the unsaturated zone and lower permeability strata above the water table. Results from the modeling show that infiltrating discharge from the TWIS will mound up to the ground surface beneath the TWIS, even using KEMC's unrealistically low mine inflow rates. Our modeling also shows that the degree of mounding above low permeability material beneath the TWIS depends to a large degree on the lateral extent and configuration of the low permeability material. KEMC has not adequately characterized the extent or configuration of these low permeability strata.

Modeling unsaturated zone flow conditions has been conducted for many decades and is standard practice in hydrogeologic studies. KEMC should have conducted unsaturated zone flow modeling to assess the effects of shallow, low-permeability strata on the infiltration of TWIS discharge. Many unsaturated zone codes are publicly available and easy to implement. VS2DHI is a free USGS code (USGS, 2004) that can be readily used to assess the effects of shallow, low-permeability units on infiltrating WWTP effluent beneath the TWIS.

A sample unsaturated flow problem was set-up using VS2DHI to illustrate how saturation buildup above low permeability layers beneath the TWIS can reach the ground surface, using reasonable hydraulic properties and the proposed KEMC TWIS dimensions and infiltration rate. Table 4.2 summarizes the occurrence of the first low permeability soil occurring in boreholes below the TWIS and the overlying soil matrix material. Boreholes locations are shown in Figure 4.15.

To simulate flow through the unsaturated zone at the proposed recharge rates requires appropriate hydraulic properties for each soil material type listed. Because these units were not tested at the site (nor were standard geotechnical tests conducted), published values from standard hydrogeologic literature are summarized in Table 4.3.

**Table 4.2. Summary of the shallowest low permeability strata beneath the TWIS using nine boreholes**

| Borehole | Depth to first low permeability material zone (ft bgs) | Low permeability material type | Saturation | Matrix material above low permeability zone |
|---|---|---|---|---|
| QAL031 | 37 to 45 | Silty sand (SM) | Unsaturated zone | Fine-medium sand (0-29 ft) Fine-sand (29-37 ft) |
| QAL008 | 76 to 84 | Silty sand/silt (SM/ML) | Saturated zone | Fine-medium sand |
| QAL036 | 73 to 75 | Silty sand (SM) | Saturated zone | Fine-medium sand |
| QAL037 | 64 to 68 | Silt (ML) | Unsaturated zone | Fine-sand (6-48 ft) |
| QAL038 | 48 to 61 | Silty sand (SM) | Unsaturated zone | Fine-medium sand |
| QAL039 | 45 to 50 | Silty sand (SM) | Unsaturated zone | Fine-medium sand |
| QAL040 | 48 to 88 | Silty sand (SM)/ML/CL | Unsaturated zone | Fine-medium sand |
| QAL041 | 30 to 45 | Silty sand (SM) | Unsaturated zone | Fine-medium sand |
| QAL042 | 36 to 38 | Silty sand (SM) | Unsaturated zone | Fine-sand (0-8 ft), fine-medium sand (8-36 ft) |

Source: Foth & Van Dyke, 2006b, Vol. 2, App. B-8, Geologic Logs.

**Table 4.3. Summary of hydraulic conductivity values for identified strata beneath the TWIS**

| Author | Soil type | m/second | m/day |
|---|---|---|---|
| Freeze and Cherry, 1979 | Clean sands (fine) | $1.00E^{-06}$ | 0.0864 |
| | Clean sands (coarse) | $1.00E^{-02}$ | 864 |
| Fetter, 2001 | Silty sands (low) | $1.00E^{-07}$ | 0.00864 |
| | Silty sands (high) | $1.00E^{-05}$ | 0.864 |
| | Silt (low) | $1.00E^{-08}$ | 0.000864 |
| | Silt (high) | $1.00E^{-06}$ | 0.0864 |
| | Glacial outwash – well-sorted sands (low) | $1.00E^{-05}$ | 0.864 |
| | Glacial outwash – well-sorted sands (high) | $1.00E^{-02}$ | 864 |

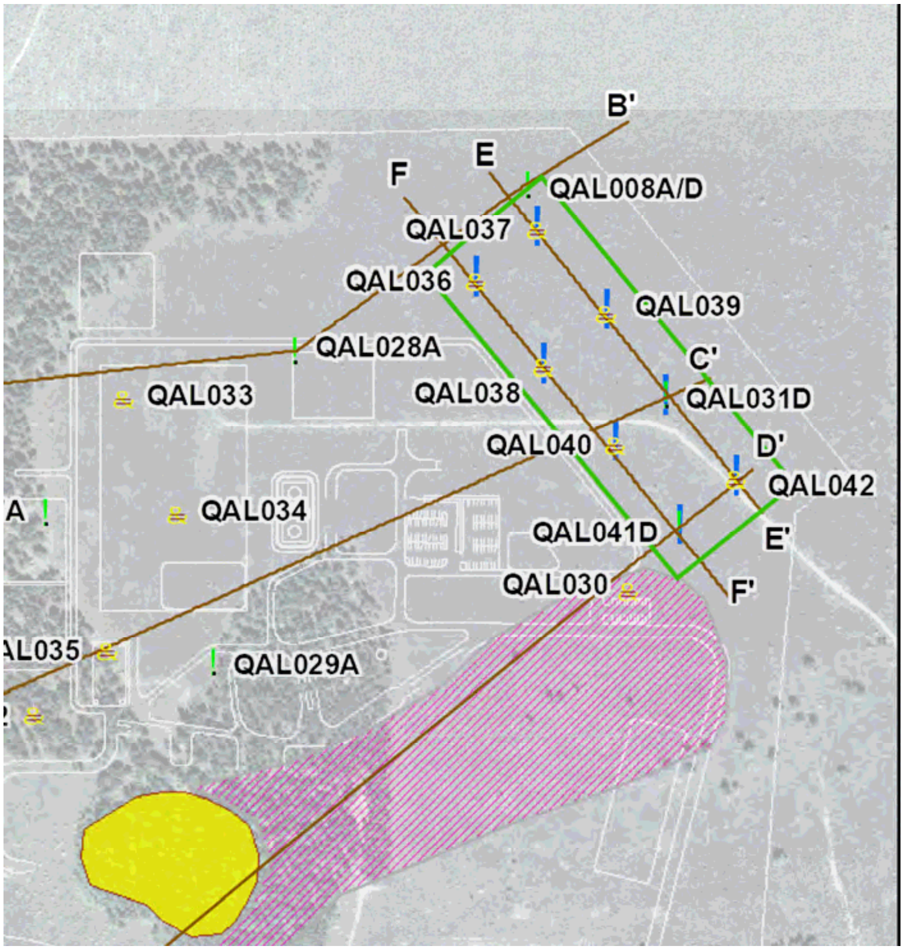


**Figure 4.15. TWIS borehole locations.**

A simple two-dimensional unsaturated zone flow model was prepared to assess potential saturation buildup above these low permeability soils. The factors affecting infiltration from the TWIS and subsequent saturation buildup over low permeability material include: recharge rate; depth, thickness, lateral extent, and hydraulic properties of the low permeability material; and the hydraulic properties of the surrounding higher permeability matrix. Details related to each factor are as follows:

- Recharge rate
  - 13 in/year – same as indicated by Cadmus (2008a). Fletcher-Driscoll used 10.8 in/year; Geotrans used 12 to 15 in/year; Golder did not specify the recharge rate.
  - 13 in/year recharge + 0.629 ft/day (400 gpm over 4/5 of 1,020 × 150 $ft^2$ infiltration area – this accounts for the fact that only 4 of 5 infiltration galleries would be operating at any given time).
- Low permeability material depth and thickness
  - Given the variability in depth of low permeability (SM) units beneath the TWIS, several configurations were simulated, including:
    - Lens from 30 to 45 ft bgs
    - Lens from 48 to 61 ft bgs.
- Low permeability material lateral extent
  - KEMC did not investigate the lateral extent, but given the occurrence of low permeability units beneath most of the length of the TWIS (1,020 ft), two shorter lengths (to be conservative in terms of predicting mounding) were evaluated:
    - 60 m (~ 197 ft)
    - 120 m (~ 394 ft).
- Low permeability material hydraulic properties
  - KEMC did not test the hydraulic properties of the low permeability soils beneath the TWIS. Therefore, based on reasonable published values from Fetter (2001), saturated hydraulic properties were assigned values similar to a silty sand (0.009 m/day). This is reasonable given the study by Koltermann and Gorelick (1995) that indicates only a few percent fines can cause hydraulic conductivity values to decrease by five orders of magnitude.

- Surrounding higher permeability matrix hydraulic properties

  - Horizontal and vertical hydraulic conductivity (Kh and Kv) values of 25 and 2.5 ft/day used for the D zone in the Golder modeling were used. However, as discussed in Section 4.4, conducting specific capacity tests on a single well (QAL031D) and then attempting to analyze these results using a confined aquifer analysis method (i.e., Cooper-Jacob) in which most underlying assumptions are violated makes this estimate highly uncertain. Because KEMC did not conduct any testing of unsaturated hydraulic properties of the more permeable matrix, these values were assumed based on reasonable published values (see Table 4.3).

  - Soils above low permeability units (see Table 4.2) are consistently described as ranging from very fine sand to fine-medium sand. Based on these descriptions, standard fine sand unsaturated zone properties were used. A value of 2.1 m/day was used for both the horizontal and vertical hydraulic conductivities of the matrix.

The basic grid and boundary conditions are shown in Figure 4.16. The ground surface elevation is shown as -40 m. In VS2DHI, negative values are assigned to elevations (heads) above the water table. The bottom of the grid is 40 m below the groundwater surface (or ~ 131 ft bgs). Groundwater levels are specified at 32 to 33 m (~ 105 to 108 ft) below the ground surface to reflect a slight gradient from left to right. These depths are similar to those observed beneath the TWIS (e.g., geologic logs in Foth & Van Dyke, 2006b, App. B-8).

The grid in Figure 4.16 represents a vertical profile perpendicular to the long-axis of the TWIS. To take advantage of the symmetry of the problem, only half of the 150-ft (~ 46 m) wide TWIS is shown at the left side of the model. A combined recharge rate of 0.1927 m/day is assigned to the TWIS infiltration gallery over this distance. A low permeability lens, 197 ft (60 m) in length from the left edge of the grid is shown as a light blue line in the figure. The surrounding yellow represents the more permeable "sand" matrix. The vertical scale has been exaggerated about five times.


**Figure 4.16. Two-dimensional unsaturated zone grid, material zones, and boundary conditions for two-dimensional unsaturated zone flow model.** The grid represents a vertical profile perpendicular to the long-axis of the TWIS. Green line = ground surface with the TWIS infiltration gallery on the left between two small white squares; light blue area = low permeability unit; dark blue lines = constant-head boundary conditions to simulate 1 m drop in head (h = 8 to h = 7) over the 250-m horizontal distance. Q = 0 are no-flow boundaries above the water table. The water table is at the bottom of the grid. Horizontal and vertical measurements are in meters.

Results of the simulation show the following:

- *TWIS discharge reaches ground surface*. Saturation reaches the ground surface for a number of reasonable configurations and parameter values for the unsaturated zone matrix and low permeability lens (Figures 4.17 and 4.18, top left sides of figures). Modeling shows that longer lengths and shallower depths of the lens cause mounding to occur faster and saturate a greater projected surface area than for the case shown. All possibilities were not assessed, but our modeling clearly demonstrates that the hydraulic characteristics of the unsaturated zone and its response to operational TWIS conditions should have been thoroughly investigated by KEMC.

- *KEMC's infiltration tests at the TWIS were not long enough.* KEMC, in its August 2008 letter to U.S. EPA (KEMC, 2008a, p. 3), stated that it was "unlikely" that a fully saturated condition would exist near the ground surface as a result of TWIS discharge. This statement was based on KEMC's infiltration tests, which KEMC stated showed that steady flow rates would be achieved "relatively quickly." KEMC's consultants conducted infiltrometer testing for generally less than two hours, and then, based on visual observation alone, concluded that water flow from the TWIS was strongly vertical with negligible evidence of horizontal flow (Foth & Van Dyke, 2006b, App. B-8, p. 29). Our unsaturated zone modeling demonstrates that it takes months for flow conditions in the unsaturated zone to reach a steady saturation profile beneath the TWIS. KEMC should have conducted the infiltration tests for longer (weeks or longer), used laboratory analyses to confirm the saturation levels, and measured saturation before and after the infiltration tests. In addition, infiltration tests should have been conducted over a larger area (similar to the size of TWIS), to limit lateral losses due to capillarity. Using a smaller area, as KEMC did, will overestimate actual infiltration rates.

- *Mounding will be higher than predicted by KEMC.* The presence of shallow, low-permeability strata will perch TWIS discharge over these units. Because these units were not considered by KEMC, mounding will likely be higher than predicted by KEMC. Mounding will occur along localized linear zones associated with drainage of overlying lenses that pinch out. Instead of considering the effect of mounding, KEMC assumed that all recharge was equally distributed over the TWIS infiltration area, and this assumption underestimates actual drainage into groundwater.

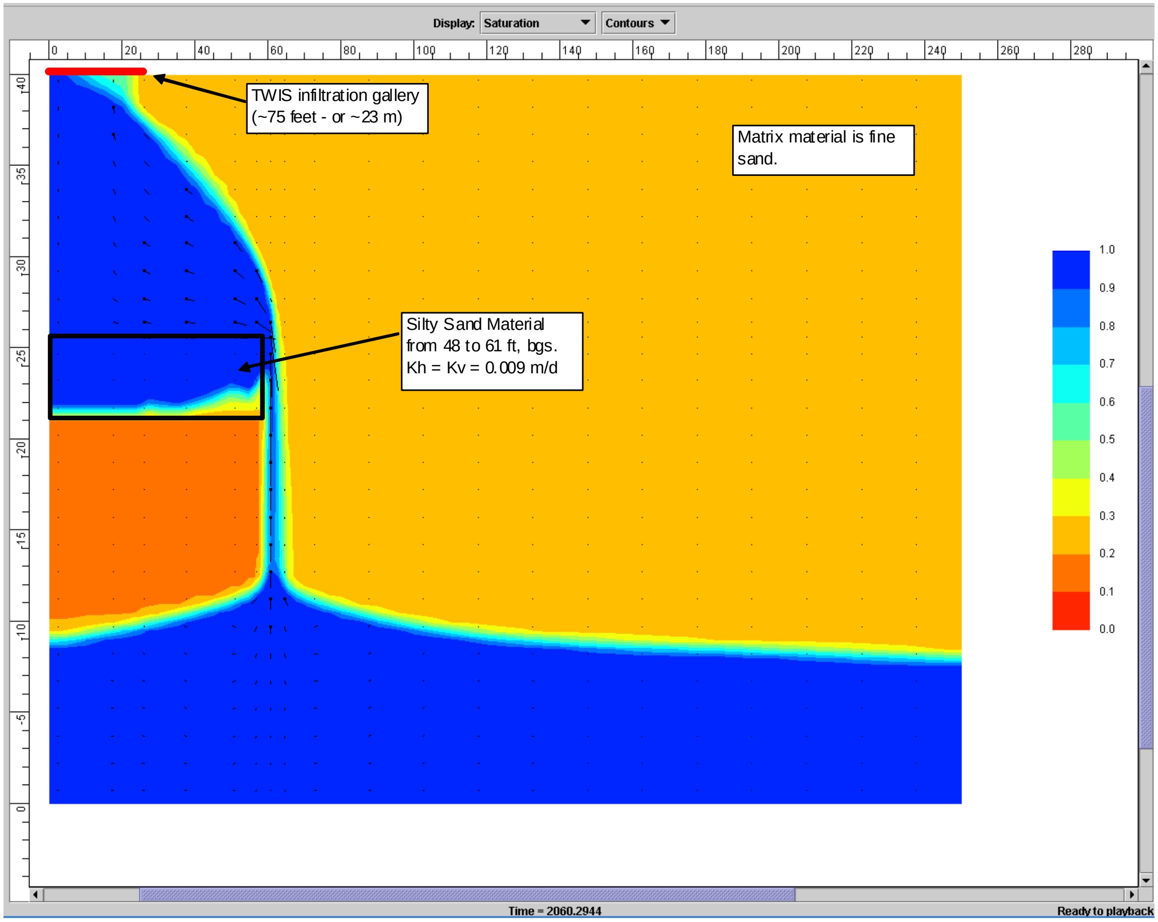


**Figure 4.17. Simulated results after 60 days of infiltration of TWIS discharge at 400 gpm into a fine sand matrix, with a 60-m long silty sand (SM) lens (black box on left) beneath the TWIS from 48 to 61 ft bgs (similar to lithology reported in borehole QAL038).** Degree of saturation is shown on colored scale; darkest blue is fully saturated.

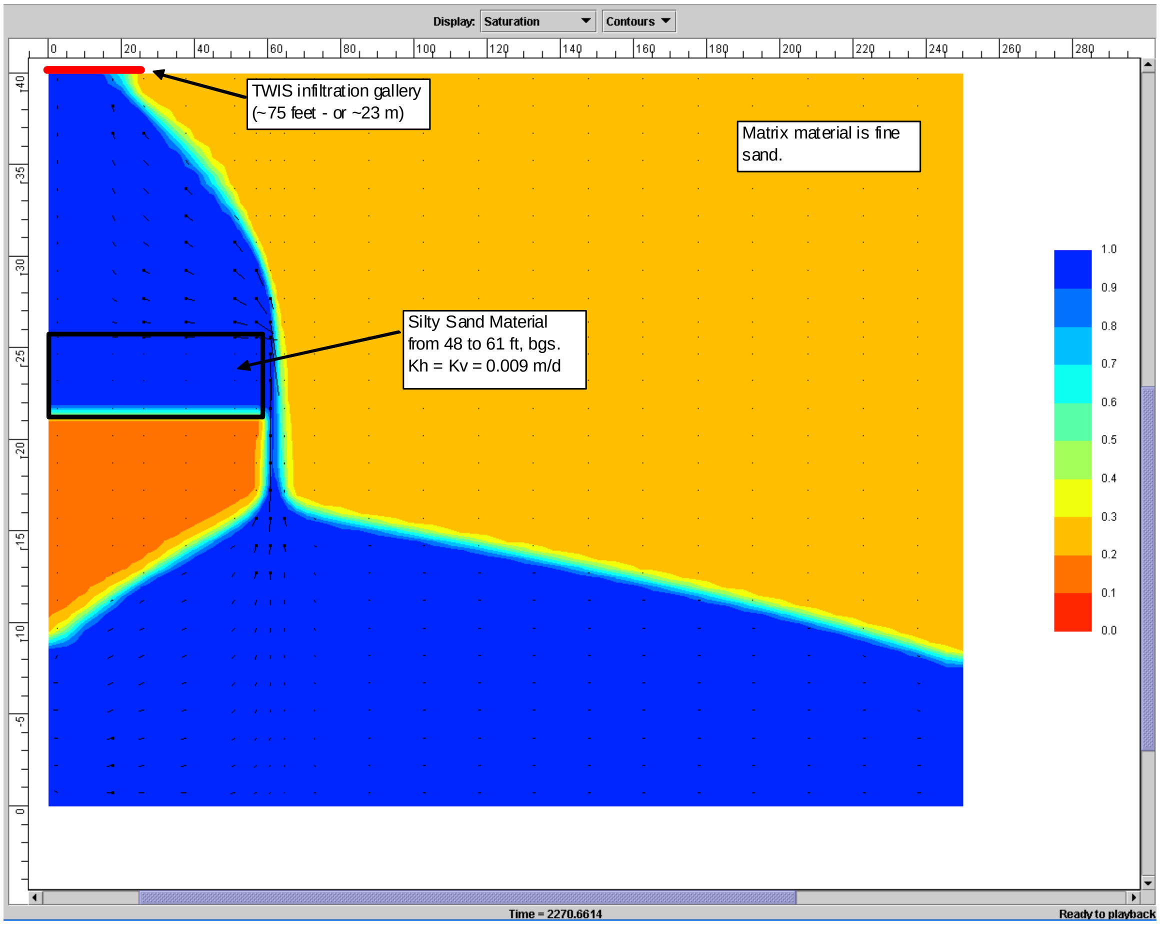


**Figure 4.18. Simulated results after 270 days of infiltration of TWIS discharge at 400 gpm.**

In summary, simple two-dimensional unsaturated zone flow modeling showed that the TWIS discharge could easily mound on lower permeability lenses, even if they are composed of silty sand. If the low permeability lenses are more laterally continuous beneath the TWIS or are composed of even lower permeability material (e.g., clay), mounding will be even more pronounced than shown in our model results. KEMC should deny the permit because of the lack of information on hydraulic properties and stratigraphy of the unsaturated zone beneath and downgradient of the TWIS. Without this type of information, an effective monitoring system cannot be designed that will be protective of the USDW in the vicinity of the TWIS.

# 4.6 The Proposed Monitoring System Will Not Protect Groundwater at the TWIS

KEMC's proposed groundwater monitoring well locations are shown in the MPA (Foth & Van Dyke, 2006b, Figure 6-1) and the Groundwater Discharge Permit (MDEQ, 2007, Figure 1, p. 29). The proposed design of the TWIS groundwater monitoring well network is flawed because it is based on flawed characterization and conceptualization of the saturated and unsaturated flow systems in the TWIS area. The monitoring system does not account for the effects of shallow low permeability material in the unsaturated zone beneath the TWIS, the magnitude of rising water levels in the Quaternary glacial aquifer, or the direction of groundwater flow.

## 4.6.1 Unsaturated zone low permeability units

The prevalence of shallow low permeability material well above the water table in all but two of the nine boreholes beneath the TWIS will cause infiltrating TWIS discharge to mound over these units. As a result, wells screened over the current water table directly beneath the TWIS will likely miss most if not all of the infiltrating TWIS discharge. At a minimum, KEMC should have proposed a monitoring network that screens across these important low permeability zones.

Our unsaturated zone flow modeling (see Section 4.4) clearly shows that infiltrating discharge from the TWIS can easily buildup above low permeability strata. Such a buildup could cause two different scenarios:

1. The buildup of saturation will migrate to the edge of low permeability strata at some distance from the TWIS and then infiltrate to the A/D aquifer zone groundwater table, where it would cause localized mounding.

2. The buildup of saturation will never migrate to the edge of low permeability strata, if they do not pinch out. KEMC presented no geologic information on the extent of low permeability strata in the TWIS area. If this scenario exists, TWIS discharge will migrate downgradient and reach surface water more rapidly.

As the TWIS discharge infiltrates beneath the TWIS and then mounds over low permeability units, it will start to flow laterally. Lateral flow will continue until the low permeability material pinches out. Whether the mounded discharge water actually reaches the current water table depends on the three-dimensional configuration, lateral extent, and hydraulic properties of the low permeability strata. This type of information must be collected and analyzed before a protective monitoring system can be designed.

### 4.6.2 Rising water levels

The proposed construction of the TWIS groundwater monitoring wells is flawed because it does not account for rising water levels in the Quaternary glacial aquifer. TWIS groundwater monitoring wells are planned to have a 10-ft screen that intercepts the existing water table. However, discharge from the TWIS is predicted to raise the water table by ~ 40 ft (Foth & Van Dyke, 2006a, p. 14) due to mounding. Therefore, a screen interval of only 10 ft at the current water table will be up to 30 ft below the ultimate possible groundwater table and may not capture much of the discharged TWIS water that will be the cause of the mounding.

To ensure that the overall chemistry of the groundwater downgradient of the TWIS is being monitored, compliance monitoring wells should be screened at two depths: one at the current water table, as proposed, and another screened from the current water table to ~ 40 ft above the current water table. The well with the larger screen should be sampled at the top of the water table at the time of sampling to capture the added water from the TWIS and to allow for measurement of groundwater mounding (elevations) over time. KEMC should revise the well construction to account for these issues.

### 4.6.3 Groundwater flow directions

Natural groundwater flow directions from the TWIS area are inferred from upgradient information and are highly uncertain because no boreholes or wells were constructed in the area of assumed groundwater flow (see Section 4.2). Attachment V of the MDEQ (2007) groundwater permit shows KEMC's inferred northeast groundwater flow direction. Groundwater gradients shown on northwest-southeast trending cross-sections through the TWIS clearly show a strong southeast-trending gradient that is nearly double the gradient shown on plan maps with the inferred northeast flow direction. Therefore, assumed downgradient groundwater flow directions are highly uncertain and are inconsistent with the presumed northeast flow directions. As discussed in Section 4.2, KEMC's new groundwater flow direction map for the A zone (KEMC, 2008c, Figure 2) also shows an east-southeast flow direction. If groundwater flow is indeed to the east-southeast, more monitoring wells are needed to the east and southeast of the TWIS, and monitoring of surface water to the east and southeast of the TWIS should also be added to the monitoring program.

In addition, the likely effects of large structural features (see Section 4.1) on groundwater flow from the TWIS were never investigated. Yet these structural features likely strongly influence groundwater flow directions from the TWIS. More investigation of the existing and potential future (mining) groundwater flow directions must be conducted before a sound groundwater monitoring plan can be designed. As part of this investigation, additional groundwater monitoring locations should be proposed, including monitoring wells downgradient of the non-contact water basins.

## 4.7 MDEQ's Groundwater Discharge Permit is Not Protective of Groundwater Quality

Unless U.S. EPA requires compliance with relevant health-based water quality standards as part of the UIC permit for the Eagle Project, the only groundwater standards that will apply are the State's groundwater discharge permit limits. Even though the MDEQ permit limits are similar to federal drinking water standards, very few of the limits are applied at the point of discharge. Table 4.4 shows KEMC's expected WWTP effluent concentrations and the permit limits that apply at the point of discharge (final effluent permit limit) and in downgradient groundwater. Of the 18 parameters in Table 4.4, only four have numeric limits applied at the point of discharge.

The MDEQ groundwater discharge permit (MDEQ, 2007) has a condition for notification of changes in discharge (MDEQ, 2007, p. 14). If any chemical listed in Attachment I of the permit is detected in the effluent at concentrations greater than five times the Expected Effluent Quality (see Table 4.4, KEMC expected effluent), KEMC must notify MDEQ in writing within 10 days of receiving the analytical results. MDEQ would then evaluate the data and notify KEMC in writing if any additional monitoring, treatment or other corrective actions are necessary. This condition in the permit allows a number of drinking water standards to be exceeded for periods of weeks to month in the effluent, taking into account analytical laboratory turnaround times, time for evaluation, writing, and mailing in both directions, and time for correcting the problem. During this extended period of time, the contaminated effluent will be discharging at a rate of ~ 320 gpm into a USDW aquifer that has very little capability of removing contaminants or otherwise reducing the impact to downgradient groundwater. As shown in Table 4.4, five times the expected effluent concentration exceeds state or federal drinking water standards, goals, or advisories for antimony, cobalt, lead, ammonia, and thallium. Therefore, these contaminants could easily be adversely impacting the downgradient USDW at the TWIS, given the conditions of the MDEQ permit.

The MDEQ permit contains numeric downgradient groundwater permit limits for most contaminants, as shown in Table 4.4. However, downgradient permit limits for antimony, arsenic, beryllium, boron, cadmium, cobalt, lead, nickel, ammonia, nitrate, and thallium exceed health-based state drinking water standards, MCLGs, or LHAs, as shown in Table 4.4. Therefore, the downgradient permit limits essentially allow a violation of the primary drinking water standards under 40 CFR part 141 or other health based standards that may adversely affect the health of persons. The violation of these health-based limits triggers the prohibition of fluid movement under § 144.12(a). As noted in Chapter 3, if higher inflow concentrations enter the WWTP, using KEMC-expected removal rates for the plant, a number of other constituents will also exceed relevant drinking water standards and cause additional violations of the prohibition of fluid movement.

**Table 4.4. Comparison of KEMC expected effluent concentrations and groundwater permit limits with relevant drinking water standards, goals, and advisories.** Values in bold exceed one or more drinking water standard, goal, or advisory.

| Chemical | Units | KEMC expected effluent[a] | KEMC expected effluent (x 5) | Final effluent permit limit, (max daily / avg. monthly) | Downgradient groundwater permit limits | Part 201 | Part 22 standards | MCL | SMCL | MCLG | Lifetime health advisory (LHA) | Expected effluent or permit limit exceeds standard? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | μg/L | 1.9 | 9.5 | Report | NA | 50 | 150 | | 50 to 200 | | | No |
| Antimony | μg/L | 1.0 | **5.0** | Report | **5.0** | 6 | 3 | 6 | | 6 | 6 | Yes: Part 22 |
| Arsenic | μg/L | NA | NA | **10 / 6.0** | **6.0** | 10 | 5 | 10 | | 0 | | Yes: Part 201, MCL, MCLG |
| Beryllium | μg/L | 0.1 | 0.3 | Report | **3.0** | 4 | 2 | 4 | | 4 | | Yes: Part 22 |
| Boron | μg/L | NA | NA | **285** / report | **285** | 500 | 250 | | | | 1,000 | Yes: Part 22 |
| Cadmium | μg/L | NA | NA | **5 / 3.0** | **3.0** | 5 | 2.5 | 5 | | 5 | 5 | Yes: Part 201, Part 22, MCL, MCLG, LHA |
| Chloride | mg/L | 44.0 | 220 | Report | 250 | 250 | 250 | | 250 | | | No |
| Cobalt | μg/L | 9.3 | **47** | Report | **23** | 40 | 20 | | | | | Yes: Part 201 |
| Copper | μg/L | NA | NA | 21 / 10 | 10 | 1,000 | 500 | 1,300[b] | 1,000 | | | No |
| Iron | μg/L | 3.2 | 16.0 | Report | NA | 300 | 300 | | 300 | | | No |
| Lead | μg/L | **0.5** | **2.5** | Report | **3.0** | 4.0 | 2 | 15[b] | | 0 | | Yes: Part 22, MCLG |
| Manganese | μg/L | 2.4 | 12.0 | Report | 50 | 50 | 50 | | 50 | | 300 | No |
| Nickel | μg/L | 4.9 | 24.5 | Report | **57** | 100 | 50 | | | | 100 | Yes: Part 22 |
| Ammonia | mg/L as N | 2.33 | **11.6** | Report | **10** | 10 | 5 | | | | | Yes: Part 201, Part 22 |
| Nitrate+ Nitrite | mg/L as N | 0.03 | 0.2 | Report | **10** | 10 | 5 | 10 | | 10 | | Yes: Part 201, Part 22, MCL, MCLG |

**Table 4.4. Comparison of KEMC expected effluent concentrations and groundwater permit limits with relevant drinking water standards, goals, and advisories (cont.).** Values in bold exceed one or more health-based standard.

| Chemical | Units | KEMC expected effluent[a] | KEMC expected effluent (x 5) | Final effluent permit limit, (max daily / avg. monthly) | Downgradient groundwater permit limits | Part 201 | Part 22 standards | MCL | SMCL | MCLG | Lifetime health advisory (LHA) | Expected effluent or permit limit equals or exceeds standard? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sulfate | mg/L | 1.7 | 8.5 | Report | 250 | 250 | 250 | | 250 | | | No |
| Thallium | μg/L | 0.4 | **2.0** | Report | **1.0** | 2.0 | 1 | 2 | | 0.5 | 0.5 | Yes: Part 201, Part 22, MCL, MCLG, LHA |
| Zinc | μg/L | 18.0 | 90.0 | Report | 1,200 | 2,400 | 1,200 | | 5,000 | | 2,000 | No |

Part 201: Residential Drinking Water Criteria, Table 1 R 299.5744.

Part 22 Standards: Appendix G1, Eagle Project Groundwater Discharge Permit Application, Kennecott Eagle Minerals Company, February 2006. Part 22 standard for arsenic was changed to 0.005 mg/L to reflect the new lower Part 201 standard of 0.010 mg/L.

MCL = maximum contaminant level; SMCL = Secondary maximum contaminant level; MCLG: maximum contaminant level goal. TT = Treatment technique. See U.S. EPA, 2006.

a. MDEQ, 2007. Attachment 1.

b. Treatment technique.

Source for MCL, SMCL, MCLG, and LHA values: U.S. EPA, 2006, 2007.

U.S. EPA requested additional information from KEMC on the chemistry of groundwater closer to the TWIS (U.S. EPA, 2008). KEMC responded by installing new wells near the TWIS and sampling them for a period of six months. Results of the groundwater sampling were presented in KEMC's November 14, 2008 submittal to U.S. EPA (KEMC, 2008b). Appendix F of the KEMC report contains a statistical analysis of the new groundwater data, but that appendix was not available at the time of this report. U.S. EPA noted that previous Quaternary groundwater quality data were collected from wells over a mile from the TWIS, and they requested that wells be installed closer to the TWIS, which KEMC did do, and that the resulting water quality data be discussed along with the data submittal. The report submitted by KEMC on this matter does not include a discussion of the data. It is merely a data report and does not compare the new results with the existing Quaternary water quality data (available in Foth & Van Dyke, 2006a, App. D). We compiled in Table 4.5 the new data for four parameters of interest: SC, alkalinity, hardness (calcium and magnesium), and arsenic.

Table 4.5 contains groundwater quality data for the new A-zone and D-zone wells, the existing A- and D-zone water quality data, and water quality data from the mainstem Salmon Trout River and the East Fork Salmon Trout River. The data shown in Table 4.5 are mean concentrations. The results show that water quality is good in the A and D zones of the aquifer, confirming that the USDW contains high quality water.

Mean values for the existing Quaternary groundwater data (GDPA, App. D) are compared to results for the new wells in Table 4.4. A-zone groundwater sampled closer to the TWIS (new wells) had somewhat higher alkalinity, hardness, and arsenic than previous samples. However, in the D-zone wells, concentrations are lower in the recent data than for the previous data. Based on these results, it is possible that D-zone water quality is fresher closer to the TWIS than at other locations.

Constituent concentrations in the A zone groundwater are similar to those in upstream mainstem Salmon Trout River (see Table 4.5). The low alkalinity and hardness values in the shallow aquifer, into which the TWIS discharge may flow, suggest that interactions of the discharge with the aquifer material will not provide buffering or hardness and that the aquifer cannot be relied upon to attenuate contaminants released from the TWIS. It is therefore imperative that contaminant concentrations are controlled at the point of discharge from the WWTP.

**Table 4.5. Summary of Quaternary aquifer groundwater quality data from KEMC's new submittal and comparison to previous data (mean values) and Salmon Trout River water quality**

| | n | Specific conductance µS/cm | Alkalinity (bicarbonate only) mg/L ($CaCO_3$) | Hardness mg/L ($CaCO_3$) | Arsenic[c] µg/L |
|---|---|---|---|---|---|
| A-zone wells | | | | | |
| QAL008A | 6 | 61 | 24 | 25 | < 1.0 |
| QAL026A | 6 | 34 | 13 | 12 | < 1.0 |
| QAL029A | 6 | 54 | 35 | 20 | 2.1 |
| QAL052A | 5 to 6 | 127 | 65 | 59 | 0.6 |
| QAL053A | 5 to 6 | 109 | 61 | 54 | 7.1 |
| QAL050A | 5 to 6 | 74 | 42 | 38 | 0.9 |
| QAL051A | 5 | – | 60 | 45 | 1.2 |
| QAL055A | 6 | 79 | 38 | 34 | 1.4 |
| QAL056A | 5 to 6 | 54 | 28 | 27 | < 1.0 |
| QAL057A | 6 | 72 | 37 | 32 | < 1.0 |
| Overall mean, new A-zone wells | 60 (approx) | 74 | 40 | 35 | 1.5 |
| Previous A-zone mean value[a] | 8 | NA | 24 | 23 | 1.1 |
| Salmon Trout River[b] | 17 | 60 | 29 | 27 | 0.5[d] |

**Table 4.5. Summary of Quaternary aquifer groundwater quality data from KEMC's new submittal and comparison to previous data (mean values) and Salmon Trout River water quality (cont.)**

| | n | Specific conductance µS/cm | Alkalinity (bicarbonate only) mg/L ($CaCO_3$) | Hardness mg/L ($CaCO_3$) | Arsenic[c] µg/L |
|---|---|---|---|---|---|
| D-zone wells | | | | | |
| QAL008D | 6 | 105 | 53 | 47 | 3.8 |
| QAL026D | 5 to 6 | 60 | 31 | 29 | < 1.0 |
| QAL029D | 6 | 103 | 65 | 53 | 2.1 |
| QAL051D | 6 | 129 | 66 | 55 | 3 |
| QAL057D | 6 | 124 | 65 | 52 | 4.9 |
| Overall mean, new D-zone wells | | 104 | 56 | 47 | 2.9 |
| Previous D-zone mean value[a] | 8 | NA | 77 | 69 | 4.6 |

a. Foth & Van Dyke, 2006a, Appendix D.
b. Data from Foth & Van Dyke, 2006b, App. B-1, Table 7; sample STRM002 (mainstem).
c. Half of the value of the detection limit was used for non-detect samples in calculating the mean.
d. All values were below the detection limit 1.0 µg/L, the average is calculated using half the value of the detection limit for all non-detect samples.

NA = not determined.

## 4.8 The MDEQ's Groundwater Discharge Permit is Not Protective of Surface Water Quality

Although UIC rules do not direct a UIC permit applicant to address surface water, the groundwater that discharges at the TWIS will vent to surface water in a relatively short distance.

Table 4.6 compares expected effluent quality and final effluent and downgradient permit limits with State of Michigan standards for surface water. The standards presented are relevant to groundwater that may discharge to surface water, and they are applied at the groundwater-surface water interface (GSI). A number of the standards are hardness-dependent, including barium, beryllium, cadmium, chromium, copper, nickel, silver, and zinc. We calculate the GSI standards using hardness values of 50 and 30 mg/L as $CaCO_3$ to reflect the possible range of hardness values in Quaternary groundwater (see Table 4.5). Discharge from the TWIS will have low hardness values (effluent/discharge concentrations in Foth & Van Dyke, 2006a, App. G1 are 26 mg/L calcium and 17 mg/L magnesium, but respective concentrations in App. G2 are 0.03 and 0.12 mg/L). As shown in Table 4.6, MDEQ's permit limits in the effluent and downgradient groundwater allow violations of surface water/GSI standards for barium, beryllium, cadmium, chromium, copper, nickel, silver, and zinc.

As noted in the Section 4.7, most of the constituents in the groundwater discharge permit (MDEQ, 2007) do not have a numeric average monthly limit for the effluent, but where they do, the limits are identical to downgradient groundwater permit limits, and these values are still higher (less protective) than surface water standards. Because so many of the constituents do not have a numeric effluent limit, the downgradient groundwater permit limits, which are the second line of defense, must also be examined. Of the nine constituents listed in Table 4.6, eight of them have downgradient permit limits that are higher than surface water/GSI standards. For example, allowable groundwater zinc concentrations downgradient of the TWIS are over 18 times higher than the surface water/GSI standard at 50 mg/L hardness. The MDEQ permit limits, therefore, do not provide an adequate early warning system for surface water.

## 4.9 Summary

KEMC's characterization of the hydrogeology in the TWIS area is poor. Because of the lack of important characterization information, KEMC is unable to accurately identify the geologic setting, the extent of the hydrogeologic units in the TWIS area, or even the direction of groundwater flow. The major hydrogeologic characterization issues include: No boreholes or groundwater monitoring wells were completed in the area from the TWIS discharge point to KEMC's expected venting location; missing or inaccurately interpreted information showing the presence of low permeability strata well above the water table; and inadequate hydraulic and geotechnical testing.

**Table 4.6. Comparison of expected effluent quality, final effluent permit limits, and downgradient permit limits with State of Michigan surface water/GSI standards.** Values in bold exceed surface water standards.

| Parameter | Units | KEMC expected effluent quality[a] | KEMC expected effluent quality x 5[a] | Final effluent permit limits (max daily/ avg monthly)[b] | Downgradient GW permit limits (max daily) | Surface water final chronic value (FCV) standard at GSI (50 mg/L/30 mg/L hardness)[d,e] | Expected effluent or permit limits exceed surface water/GSI standard? |
|---|---|---|---|---|---|---|---|
| Barium | µg/L | 1.4 | 7 | Report | **1,000** | 210 / 120 | Yes |
| Beryllium | µg/L | 0.05 | **0.25** | Report | **3** | 0.41 / 0.11 | Yes |
| Cadmium | µg/L | 0.6[c] | **3** | **5 / 3** | **3** | 1.3 (2.8) / 0.92 | Yes |
| Chromium | µg/L | 0.5 | 2.5 | Report | **52** | 42 / 28 | Yes |
| Copper | µg/L | –[c] | – | **21 / 10** | **10** | 5.0 (7.4) / 3.2 | Yes |
| Nickel | µg/L | 4.9 | **24.5** | Report | **57** | 29 / 19 | Yes |
| Selenium | µg/L | –[c] | – | **25** / 5 | 5 | 5 | No |
| Silver | µg/L | –[c] | – | **17 / 0.4** | **0.4** | 0.2 (0.3) | Yes |
| Zinc | µg/L | 18 | **90** | Report | **1,200** | 66 / 43 | Yes |

GSI = groundwater-surface water interface; GW = groundwater; Avg = average.

a. Groundwater Discharge Permit (GWDP; MDEQ, 2007, p. 14); If effluent concentrations are >5 times the Expected Effluent Quality, the permittee shall notify the Department, in writing, within 10 days.

b. Expected Effluent Quality and Maximum Daily and Average Monthly effluent limits are from GWDP. Note that downgradient groundwater permit limits are only Maximum Daily Limits.

c. Not listed in Attachment I of GWDP.

d. MDEQ, (at hardness of 50 mg/L and 30 mg/L) www.deq.state.mi.us/documents/deq-erd-opmemo18-%7BG%7D.xls.

e. Values in parentheses are from October 26, 2006 MDEQ memorandum from LeSage to Chatterson, Re: Venting groundwater review comments (Exhibit 188).

KEMC's prediction of groundwater flow direction ignores the existing hydrogeologic information and is highly uncertain. KEMC assumed, based on very little information, that groundwater will flow in a northeasterly direction from the TWIS. KEMC later modified the groundwater flow direction in its maps submitted to U.S. EPA without collecting additional information on groundwater elevations in critical areas.

KEMC failed to consider the effect of major hydrogeologic basin features (dikes, faults, major surface drainage features) on groundwater flow conditions in the TWIS discharge area and in areas potentially affected by this discharge.

We conducted simple two-dimensional unsaturated zone flow modeling using the available information from the logs. Results from the modeling showed that infiltrating discharge from the TWIS will mound up to the ground surface beneath the TWIS, even using KEMC's unrealistically low assumed mine inflow rates. Our modeling also shows that the degree of mounding above low permeability material beneath the TWIS depends to a large degree on the lateral extent and configuration of the low permeability material. KEMC has not adequately characterized the extent or configuration of these low permeability strata.

The proposed design of the TWIS groundwater monitoring well network is flawed because it does not account for the effects of shallow low permeability material in the unsaturated zone beneath the TWIS, or the magnitude of rising water levels in the Quaternary glacial aquifer or the direction of groundwater flow.

The MDEQ's groundwater discharge permit is not protective of groundwater quality. Effluent limits in the MDEQ permit allow antimony, cobalt, lead, ammonia, and thallium to exceed drinking water standards in the effluent for periods of weeks to months. Similarly, downgradient permit limits for antimony, arsenic, beryllium, boron, cadmium, cobalt, lead, nickel, ammonia, nitrate, and thallium exceed health-based state drinking water standards, MCLGs, and LHAs. Our analysis shows that the discharge will likely violate the prohibition of fluid movement because the expected effluent concentrations and the permit limits are less protective than relevant state and federal drinking water standards, goals, and advisories.

KEMC's new information on groundwater quality in the vicinity of the TWIS demonstrate that water quality is good in the A and D zones of the aquifer, confirming that the USDW contains high quality water. Constituent concentrations in A zone groundwater are similar to mainstem Salmon Trout River water quality, suggesting that interactions of the discharge with the aquifer material will not provide buffering or hardness and that the aquifer cannot be relied upon to attenuate contaminants released from the TWIS. It is therefore imperative that contaminant concentrations are controlled at the point of discharge from the WWTP.

The MDEQ'groundwater discharge permit is not protective of surface water quality. Although the UIC rules do not direct a UIC permit applicant to address surface water impacts, the groundwater that discharges at the TWIS will vent to the surface water in a relatively short distance. MDEQ's effluent and downgradient permit limits allow violations of surface water / GSI standards for barium, beryllium, cadmium, chromium, copper, nickel, silver, and zinc. For example, allowable groundwater zinc concentrations downgradient of the TWIS are over 18 times higher than the surface water/GSI standard at 50 mg/L hardness. The MDEQ permit limits, therefore, do not provide an adequate early warning system for surface water.

# References

Anderson, M. P. and Woessner, W.W. 1992. *Applied Groundwater Modeling. Simulation of Flow and Advective Transport*. Academic Press. 381 pp.

ASTM 2002. D 5979-96 (Reapproved 2002), Standard Guide for Conceptualization and Characterization of Ground-Water Systems. ASTM International, West Conshohocken, PA.

ASTM. 2005. ASTM D5472-93 (2005) Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well.

Butler, J.J. and J.M. Healey. 1998. Relationship between pumping-test and slug-test parameters: Scale effect or artifact. March. *Ground-Water* 36(2):305-313.

Cadmus. 2008a. Class V Treated Water Infiltration System Application Review – Final Report. The Cadmus Group. Prepared for U.S. Environmental Protection Agency, Region 5. June 12.

Cadmus. 2008b. Comments on Responses to Request for Additional Information (Class V Treated Water Infiltration System Application): Final Report. The Cadmus Group. Prepared for U.S. Environmental Protection Agency, Region 5. Undated.

Eary, L.E. 2006. Review of geochemistry studies for the Kennecott Eagle Project permit application. Prepared for State of Michigan Department of Environmental Quality. November 30.

Fetter, C.W. 2001. *Applied Hydrogeology*, Fourth Edition, Prentice Hall, NJ. 598 pp.

Foose, M.P., M.L. Zientek, and D.P. Klein. 1995. Magmatic sulfide deposits. In *Preliminary Compilation of Descriptive Geoenvironmental Mineral Deposit Models*, E.A. du Bray (ed.). U.S. Geological Survey Open-File Report 95-831.

Foth & Van Dyke. 2006a. Eagle Project Groundwater Discharge Permit Application. Prepared for Kennecott Eagle Minerals Company by Foth & Van Dyke and Associates, Inc. February.

Foth & Van Dyke. 2006b. Eagle Project Mining Permit Application. Prepared for Kennecott Eagle Minerals Company by Foth & Van Dyke and Associates, Inc. February. (Mine Permit Application.) Volumes 1 and 2.

Foth Infrastructure and Environment. 2007. Eagle Project Class V Permit Application. Prepared for KEMC. April.

Freeze. R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Inc., Englewood Cliffs, N.J. 604 pp.

Geochimica. 2004. Eagle Project Geochemistry Study. Appendix D-1 of the Eagle Project Mining Permit Application. June 30.

Geochimica. 2005. Technical Memorandum: Water Quality from the Development Rock Storage Pad During Operations. Prepared for Kennecott Eagle Mining Company, Appendix D-3, Mine Permit Application: TDRSA Water Chemistry. November 7.

Geotrans. 2008. A technical memorandum from Gregory Council at Geotrans, to Rod Lewis, Warner, Norcross & Judd on "Quaternary Groundwater Model, Kennecott Eagle Mine." Geotrans Inc. April 1.

Golder Associates. 2006. Appendix E-3, Mine Discharge Permit Application. Technical Memorandum titled "Groundwater Modeling of Proposed Infiltration at Kennecott Eagle Mine, Michigan."

Honigman Miller Schwartz and Cohn. 2006. Letter to U.S. EPA Region 5. Kennecott Eagle Minerals Company; Marquette County, Michigan; Proposed Underground Injection Wells. June 9.

Illman, W.A. 2006. Strong field evidence of directional permeability scale effect in fractured rock. *Journal of Hydrology* 319(1-4):227-236.

KEMC. 2008a. Letter to U.S. EPA. Kennecott Eagle Minerals Company Response to EPA's Request for Additional Information, dated October 30, 2008. Kennecott Eagle Minerals Company, UIC Permit Application Number MI-103-5W20-0002. August 21.

KEMC. 2008b. Letter to U.S. EPA. Response to EPA's Request for Additional Information, dated October 30, 2008. Kennecott Eagle Minerals Company, UIC Permit Application Number MI-103-5W20-0002. November 14.

KEMC. 2008c. Letter to U.S. EPA. Response to EPA's Request for Additional Information, dated October 30, 2008. Kennecott Eagle Minerals Company, UIC Permit Application Number MI-103-5W20-0002. November 21.

KEMC. 2008d. Letter to U.S. EPA. Response to EPA's Request for Additional Information, dated October 30, 2008. Kennecott Eagle Minerals Company, UIC Permit Application Number MI-103-5W20-0002. December 19.

Kennecott Exploration. 2005. Geology of the Eagle Nickel-Copper Deposit. Appendix C-1 in Eagle Project Mining Permit Application. Prepared by Dean Rossell and Steven Coombes. April 29.

Klasner, J.S., D.W. Snider, W.F. Cannon, and J.F. Slack. 1979. The Yellow Dog Peridotite and a Possible Buried Igneous Complex of Lower Keweenawan Age in the Northern Peninsula of Michigan. State of Michigan, Dept. of Natural Resources, Geological Survey Division; Report of Investigation 24. 31 pp.

Koltermann, C.E. and Gorelick, S.M. 1995. Fractional Packing Model for Hydraulic Conductivity Derived From Sediment Mixtures. *Water Resources Research* 31(12):3283-3297.

Kruseman, G.P. and N.A. de Ridder. 1991. Analysis and Evaluation of Pumping Test Data. *ILRI Publication* 47:377.

MDEQ. 2007. Permit No. GW1810162, December 14. Michigan Department of Environmental Protection.

Neuman, S.P. and P.J. Wierenga. 2003. A Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear facilities and Sites. University of Arizona, NUREG/CR-6805. Prepared for Division of Systems Analysis and Regulatory Effectiveness Office of Nuclear Regulatory Research. U.S. Nuclear Regulatory Commission Washington, DC. 20555-0001 NRC Job Code W6790.

PMR. 2007. Baraga Basin. Available. http://www.primemeridianres.com/s/Baraga.asp. Accessed November 2008.

PMR. Geologic Map of the Baraga Basin Project Area. Available: http://www.primemeridianres.com/i/maps/baraga/baraga-01.jpg. Accessed November 25 2008.

Price, W. and J. Errington. 1994. ARD Policy for Mine Sites in British Columbia. Presented at International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acid Drainage, Pittsburgh, PA. p. 287.

Sainsbury, D. 2007. Summary of Technical Review Conducted on the Crown Pillar Subsidence and Hydrologic Stability Assessment for the Proposed Eagle Mine. Technical Memorandum to Hal Fitch, Michigan DEQ, March 2. Ref. ICG07-2420-10TM.

Segerstrom, K. 1964. Negaunee Moraine and the Capture of the Yellow Dog River, Marquette, Michigan. U.S. Geological Survey Research Paper 501-C. pp 126-139.

Stratus Consulting. 2007a. Geochemical Review and Water Quality Predictions for the Eagle Project, Michigan. Prepared for: F. Michelle Halley, National Wildlife Federation. August 14.

Stratus Consulting. 2007b. Comments of the Keweenaw Bay Indian Community in Opposition to the Proposed Issuance to Kennecott Eagle Minerals Company of Groundwater Discharge Permit No. GW1810162. Prepared for: Eric Eggan, Honigman Miller Schwartz and Cohn LLP. October 16.

Stuart, W.T., E.A. Brown, and B.C. Rhodehamel. 1954. Technical Report Number 3 Ground-Water Investigations of the Marquette Iron-Mining District, Michigan by U. S. Geological Survey. Prepared in cooperation with the United States Department of the Interior Geological Survey.

U.S. EPA. 2005. Region 5 Underground Injection Control Class V Permit Application Instructions. April 2005 Version. 5pp. (From: INSTRUCTIONS – Attachments / EPA Form 7520-6).

U.S. EPA. 2006. *2006 Edition of the Drinking Water Standards and Health Advisories*. EPA 822-R-06-013. Office of Water, U.S. Environmental Protection Agency, Washington, DC. August. Available: http://www.epa.gov/waterscience/criteria/drinking/. Accessed January 2009.

U.S. EPA. 2007. Drinking Water Contaminants. U.S. Environmental Protection Agency. Available: http://www.epa.gov/safewater/contaminants/index.html. Accessed January 2009.

U.S. EPA. 2008. Letter from Rebecca Harvey, EPA Region 5, to Victoria Peacey, KEMC. Request for Additional Information in support of the UIC Permit Application Number MI-103-5W20-0002. U.S. Environmental Protection Agency Region 5. October 30.

USGS. 2004. VS2DHI – Version 1.2. A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media. Available: http://wwwbrr.cr.usgs.gov/projects/GW_Unsat/vs2di1.2/index.html. Accessed November 25, 2008.

**A1. Testimony of Robert Prucha (referenced in Chapter 2). Excerpt from Hearing Transcript, Vol. 8, 9, and 40, *Petitions of the Keweenaw Bay Indian Community, et al. on Permits Issued to Kennecott Eagle Minerals Company* (Michigan Department of Environmental Quality, May 7, May 8, and July 16, 2008). (electronic only)**

**A2. Testimony of Kenzi Karasaki (referenced in Chapter 2). Excerpt from Hearing Transcript, Vol. 39, *Petitions of the Keweenaw Bay Indian Community, et al. on Permits Issued to Kennecott Eagle Minerals Company* (Michigan Department of Environmental Quality, July 15, 2008). (electronic only)**

## B. FEFLOW (referenced in Chapter 2) and VS2DHI (referenced in Chapter 4) input and output files. (electronic only)

**C. Intervenor's exhibit 214 (referenced in Chapter 2) from *Petitions Of The Keweenaw Bay Indian Community, et al. On Permits Issued To Kennecott Eagle Minerals Company* (Michigan Department of Environmental Quality)**

**D. Testimony of Glenn Miller (referenced in Chapter 3). Excerpt from Hearing Transcript, Vol. 11, *Petitions of the Keweenaw Bay Indian Community, et al. on Permits Issued to Kennecott Eagle Minerals Company* (Michigan Department of Environmental Quality, May 12, 2008). (electronic only)**

**STRATUS** CONSULTING

1881 Ninth Street, Suite 201 Boulder, Colorado 80302 phone 303.381.8000 fax 303.381.8200 (headquarters)

1920 L Street, N.W., Suite 420 Washington, D.C. 20036 phone 202.466.3731 fax 202.466.3732

www.stratusconsulting.com