resourceful. naturally.
engineering and environmental consultants
BARR

Technical Memorandum

To: Bill Johnson
From: John Swenson and Jeré Mohr
Subject: Response to questions on saline groundwater
Date: September 7, 2012
Project: NorthMet SDEIS – 23690862.00 042 002
c: Jim Scott, PolyMet

Questions have been raised by the U.S. Forest Service regarding the potential for 'saline' groundwater to be intersected by the NorthMet mine pits. Responses to these questions are provided below. The nomenclature of pore-fluid salinity can be a source of confusion. Please note that the simple classification scheme of Freeze and Cherry[1], which is based on total dissolved solids (TDS; mg/l), is used herein. In the Freeze and Cherry (1979) scheme, a *brine* is characterized by TDS in excess of 100,000 mg/l; *saline* groundwater has TDS in the range of 10,000 – 100,000 mg/l; and the TDS of *brackish* groundwater ranges from 1,000 – 10,000 mg/l. For comparison, standard seawater has TDS of approximately 35,000 mg/l. Note as well that in this common classification scheme, the majority of groundwater with elevated chloride values discussed in this document would be termed *brackish*.

Question/Comment:

The SNF has collected some samples during active drilling near the South Kawishiwi River and found elevated chloride levels. It looks like the PolyMet data shows lower chloride levels to date. I have not looked at the data collection in detail, but a couple of questions to perhaps forward to technical consultants at some point:

Is the data reflective of deeper water quality conditions?

- Not a surface grab sample from a hole that has 'set up' a salinity gradient
- Not reflective of the drilling fluid used…i.e., the hole was 'developed'

---

[1] Freeze, R.A. and J.A. Cherry, 1979. *Groundwater*. Prentice-Hall, Inc.

Response:

As part of the Phase I Hydrogeologic Investigation, groundwater samples were collected from two exploratory boreholes (05-401M and 05-407M) and the water supply well at the Mine Site (MDH Unique ID# 717972). Prior to sampling, development was completed by purging multiple borehole volumes at each exploratory borehole location. However, some remnant drilling fluid may have been present in these boreholes when the samples were collected. The procedures used to develop the water supply well are not known. However, the well was actively being used to supply water for exploration drilling at the time of sampling and was purged prior to sample collection. In addition, samples have been collected from nine monitoring wells completed in the bedrock (P-1 through P-4, Ob-1 through Ob-5). The wells were installed using air rotary drilling techniques without the use of drilling fluid. Prior to sampling, the wells are purged and stabilized. Thus, the chloride data collected to date from these wells are reflective of average groundwater conditions over the borehole/well depth.

The table below summarizes the depth of each borehole/well sampled, the number of samples collected, and the maximum chloride concentration observed at each location.

Location	Depth (feet below ground surface)	# of Chloride Samples	Maximum Chloride Concentration (mg/L)
05-401M	349	1	1.7
05-407M	354	1	2.7
Water Supply Well (MDH Unique ID #717972)	200	1	0.5
P-1	610	1	6.6
P-2	610	5	1.8
P-3	610	1	2.1
P-4	485	1	< 0.5
Ob-1	100	6	15.7
Ob-2	100	6	0.6
Ob-3	100	6	93.1*
Ob-4	100	6	0.77
Ob-5	100	6	0.63

* Value from initial sampling; maximum subsequent value was 0.81 mg/L

Question/Comment:

Will additional information be collected this year to affirm previous data?

Response:

The Bedrock observation wells ("Ob" wells) will be sampled again in September or October.

Question/Comment:

Has any deeper conductivity testing been performed? (MGS has equipment that can measure to 1,500 feet) – this could confirm freshwater through the borehole

Response:

Borehole fluid conductivity testing has not been performed.

Question/Comment:

Brackish groundwater has been identified as characteristic of the Duluth Complex, and its potential to impact fresh water via various mining activities has been raised in public comments on the Superior National Forest's draft EIS for minerals exploration. In general, the potential of encountering brackish water increases with depth. There was a documented artesian brackish borehole northeast of PolyMet in the 1970's (AMAX site). This appears to be an anomaly as there have been numerous other holes drilled in the area of PolyMet without documentation of artesian conditions. However, the connectivity, volume, salinity, and depth of brackish water near PolyMet does not appear to be a focus of investigation to date.

Response:

The closest wells to the NorthMet site that are known to have encountered groundwater with elevated chloride concentrations are located approximately 3.2 miles to the northeast of the northeast edge of the East Pit at the former AMAX mine site. Brackish water with chloride concentrations of approximately 1,500 mg/L was encountered in the test shaft at a depth of 1,194 feet, or at an elevation of approximately 400 feet MSL.[2] Non-artesian, brackish water was also encountered at a depth of approximately 1,391 feet (elevation of approximately 200 feet MSL) in drill hole DH-303 when a serpentinized fracture of gabbro

---

[2] Barr Engineering Co., 1977. Water Management Plan and Preliminary Engineering Report accompanying NPDES Permit for Minnamax Basin Discharge

was encountered (Minnamax, 1976). The minimum elevations of the East and West pit bottoms at the NorthMet site are estimated to be approximately 800 and 900 feet MSL, at least 500 feet (~150 meters) above the elevations where groundwater with elevated chloride concentrations has been observed in the area. Therefore, it is unlikely that the pits will directly intersect zones of brackish groundwater and evaluating brackish water has not been a primary focus of the investigation program.

However, dewatering of the proposed open-pit mine represents a perturbation to the equilibrium groundwater flow system that is broadly similar to that associated with the installation of a large pumped well. The drop in hydraulic head associated with pit dewatering will induce groundwater flow to the mine pits. To investigate the potential for influx of brackish groundwater to the mine pits during dewatering, two analytical models were developed to evaluate the potential for regional-scale migration of deep brackish/saline groundwater and the likelihood of these fluids to migrate and discharge to the mine over its lifespan. The model development and results are described in detail in the attached document. The analysis showed that there is some possibility that brackish groundwater could migrate into the pit during the later stages of pit dewatering.

Question/Comment:

The *impact* of brackish water interception by PolyMet is reduced based upon my understanding that there is no planned discharge from the active pit(s). It is also possible that the volume of brackish groundwater is limited and will be exhausted by the time of filling in the West Pit. However, if elevated salinity of the water is sustained, it may still be important in considering:

1. Water quality of the West Pit as part of the reclamation after it is allowed to fill
    a. it could impact the biota that would become established in the West Pit and/ or
    b. have potential downstream effects as the pit converts to an open system.
2. Though less probable, higher salinity levels could possibly affect their internal processing reactions (may mean some additional processing or make-up water to dilute)

Based upon this understanding, it is worth considering testing the groundwater from the existing boreholes for chloride, salinity or total dissolved solids. Although there may be no *ideal* way to test borehole water for salinity to full depth, testing the upper 500 feet +/- may be possible with a submersible pump. While this would not test the entire depth, it would provide information on the depth of formation that will be 'exposed' as part of the mining process.

Response:

Available regional and site data suggest that the NorthMet pits will not directly intersect groundwater with elevated chloride concentrations because it is located at elevations below the currently-planned mine depths. However, as described in the attached document, there is a small potential that pit dewatering could cause sufficient perturbation to the underlying salinity structure to allow brackish groundwater to migrate upward and discharge to the pit while it is being dewatered.

Fundamentally, the driving mechanism for potential discharge of brackish water to the mine pit is dewatering of the pit itself, which, from the perspective of the regional groundwater flow system, generates a region of anomalously low hydraulic head. It follows that abandonment and subsequent flooding of the mine act to shut off this driving mechanism and return the flow system to its pre-mine configuration. In essence, as the mine pit floods and the hydraulic-head anomaly dissipates, the salinity structure beneath the mine will relax to its pre-mining, equilibrium configuration. Therefore, any discharge of brackish groundwater to the pits that does occur would be expected during operations or in the early stages of pit flooding, when groundwater pumped from the pits will be routed to the Mine Site wastewater treatment facility. In addition, if brackish water does discharge to the pits, it would likely represent a very small proportion of the overall water inflow to the pit.

Attachment A

Regional groundwater flow model

Groundwater salinity generally increases with depth below the land surface as a result of increased residence time and elevated temperature. In sedimentary basins, brines (pore fluids with salinities greater than 100,000 mg/l) are commonly encountered in petroleum exploration wells at depths exceeding a kilometer (e.g., Hanor, 1987, 1994). On the low-relief Canadian Shield, groundwater with very high chloride concentrations (so-called 'Shield brine') is ubiquitous at depths greater than a kilometer (e.g., Rouleau et al., 2003). Brackish to saline groundwater is commonly observed in shallow (< 100 m) bedrock wells near Lake Superior and is encountered sporadically in significantly deeper (> 300 m) bedrock wells in northeastern Minnesota and on the Keweenaw Peninsula (Minnamax, 1976; Barr, 1977; Morton and Ameel, 1985; Kelly et al., 1986; Johnson et al., 1995; Swenson et al., 2002). On the basis of these observations, Barr Engineering Co. developed an idealized conceptual model for the regional salinity structure, in which a lens of fresh groundwater—fed by meteoric recharge—'floats' atop high-salinity groundwater, i.e. atop a 'parent' brine of ρ_b. Observed groundwater salinity deep within copper mines on the Keweenaw Peninsula (Kelly et al., 1986; Johnson et al., 1995) constrains the salinity of the parent (ρ_b = 1200 kg/m^3 in the model).

For the purposes of developing an analytical model of steady-state, regional-scale groundwater flow, Barr assumes an *interface* separates the freshwater lens from the underlying brine; in reality, fresh groundwater and parent brine most likely are separated by a diffuse mixing zone of poorly constrained thickness. Groundwater in this mixing zone would be characterized as saline to brackish. As a first approximation, any changes in the depth of the interface are mirrored by changes in the depth of the mixing zone. The overarching objective of the regional-scale flow model is a comparison of water-table and interface profiles under pre-mining (unperturbed) and mining conditions, where the latter is characterized by a constant discharge of groundwater to the mine pit.

The model cross section is aligned parallel to the regional-scale groundwater flow field and stretches southeastward from the Giants Range (topographic divide) to the shoreline of Lake Superior. The model treats the Giants Range divide as a no-flow boundary; Lake Superior serves as base level for the freshwater lens, and model hydraulic head is assumed equal to lake elevation at the shoreline. The flow model borrows from well-established Ghyben-Herzberg theory of saltwater intrusion beneath island aquifers. In particular, the groundwater system is assumed to be stably stratified and in isostatic equilibrium such that no lateral pressure gradients exist in the underlying parent brine beneath an appropriate compensation depth. At any point on the cross section, isostasy dictates the relation between elevation (h) of the water table (relative to base level) and thickness (H) of the freshwater lens:

$$h = \frac{(\rho_b - \rho)}{\rho_b}(H - d)$$

where ρ is the density of fresh groundwater and d is the thickness of the freshwater lens at the shoreline of Lake Superior.

With the aforementioned parent-brine density, each unit of water-table elevation is underlain by approximately six units of fresh groundwater; likewise, gradients in the water table are mirrored six-fold by gradients in the thickness of the freshwater lens. The model requires as a boundary condition the thickness of the freshwater lens at the Lake Superior shoreline. This thickness is unknown; however, the average depth of the lake (approximately 150 m) provides a physically reasonable constraint on this thickness, as it is difficult to envision a scenario in which the parent-brine interface intersects the bottom of the lake. In effect, this model assumption represents a 'worst case' scenario that *minimizes* the depth to the hypothetical parent brine.

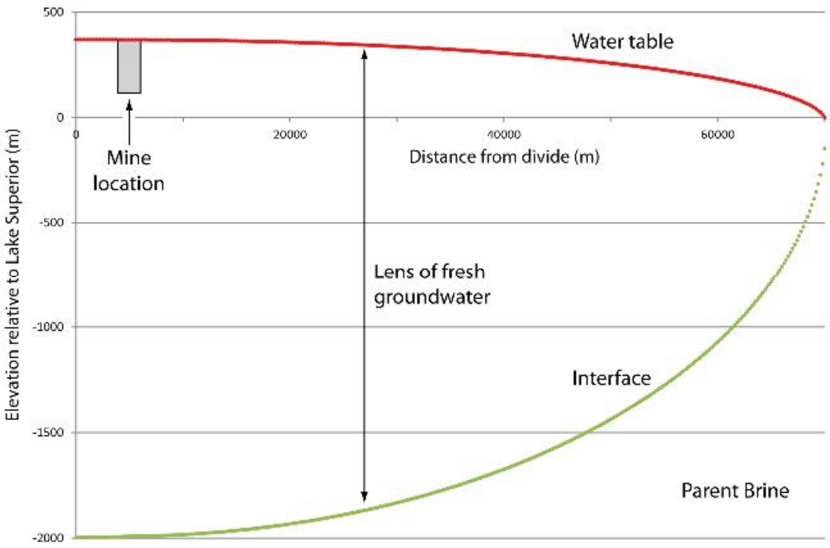

Figure 1. Model predicted elevations for the regional water-table (red curve) and corresponding interface (lower green curve) between freshwater lens and parent brine along an idealized east-west cross section. Cross section originates at the groundwater divide immediately west of the PolyMet site (Giants Range) and terminates at the shoreline of Lake Superior. Note approximate location of mine.

Groundwater flow in the freshwater lens is depth-integrated and driven by lateral gradients in the water table that arise in response to uniform regional recharge. The model amalgamates all bedrock units into a representative medium with homogeneous hydraulic conductivity. To represent the dewatered mine pit in cross section, volumetric discharge from the fully developed mine is normalized by mine width (out of the model plane) to obtain an effective cross-sectional discharge; this discharge is then applied at a point, i.e. at the regional scale and in a depth-averaged sense, the mine is treated as a fully penetrating well with steady discharge. Model recharge (2 inches/year) and estimated mine discharge (500 GPM) are informed by a separate high-resolution (mine scale) flow model constructed previously by Barr Engineering Co. Model hydraulic conductivity (~ 2 feet/day) is adjusted so that the water-table elevation under pre-mine conditions honors the overall regional topography. Note that this regional-scale bulk hydraulic conductivity is approximately two orders of magnitude larger than the calibrated conductivities from the high-resolution flow model; this 'scale effect' in hydraulic conductivity is well established in regional-scale flow models (e.g., Garven, 1995).

Under the above assumptions, the flow model has an analytical solution for the water-table elevation and corresponding interface location (Figure 1). At the regional scale of the cross section in Figure 1, the impact of the mine dewatering is difficult to discern. Figure 2 shows the difference in water-table and interface elevation for pre-mine and dewatered-mine conditions; in essence, Figure 2 shows the 'drawdown' of the water table due to dewatering the mine and the associated 'intrusion' (vertical translation) of the interface. For the parameter values listed above, dewatering the mine yields approximately 20 meters of drawdown in the water table at the mine pit (a value consistent with that of the high resolution MODFLOW model constructed by Barr), which by isostasy generates approximately 110 meters of interface translation. In the context of this idealized model, in which the parent brine is depressed more than two kilometers below the mine site, dewatering the mine pit will not result in an influx of the parent brine to the pit. In the natural system, however, the interface most likely has the form of a mixing zone of poorly constrained thickness. If translation of the mixing zone in response to mine dewatering mirrors the intrusion of the interface in the idealized model, then any brackish groundwater within approximately 100 meters of the pit floor has the potential to discharge to the mine. For reference, brackish groundwater was observed at the AMAX/Minnamax site at depths that would correspond to 120 meters and 180 meters *below* the proposed maximum depth of the NorthMet mine pits.

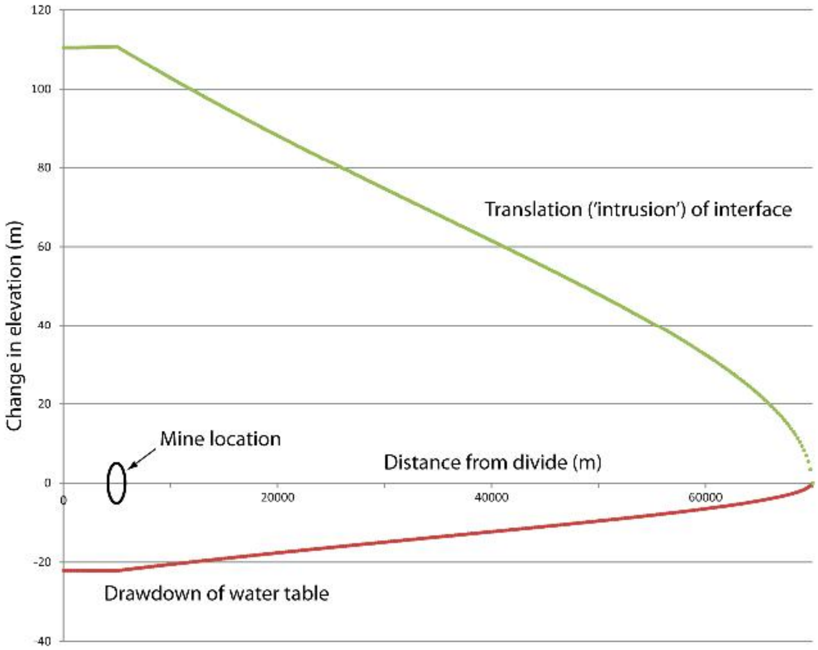

Figure 2. Model predicted perturbation to the regional-scale groundwater flow system as a result of mine dewatering along the same cross section as Figure 1. Red curve is the 'drawdown' in the water table; green curve is 'intrusion' or 'up-coning' of the freshwater-brine interface. Note that both drawdown and intrusion are greatest (in magnitude) at the mine location. Model predictions above reflect conditions when the mine depth is greatest.

Timescale for equilibration

The above flow model assumes equilibration between the dewatered mine and the underlying interface, i.e. it is a steady state model. In practice, the mine has a finite lifespan (approximately twenty years) and the possibility exists that the underlying salinity structure may have insufficient time to attain isostatic equilibrium, i.e. the hydrodynamics might lag mine development. Hence, while the equilibrium model above may predict interaction between saline groundwater and the mine pit, the time lag may be such that this interaction is never realized over the lifespan of the operation. The relevant time lag in this problem is associated with vertical advection of saline groundwater; in the context of the above conceptual model, this time lag (τ) can be approximated as the ratio of depth to interface (D_i) beneath the open pit to vertical groundwater velocity (v), i.e. $\tau \sim D_i / v$, where velocity is dictated by Darcy's Law and effective porosity (n_e) of the bedrock:

$$v \sim \frac{K_z}{n_e}\frac{\Delta h}{D_i}$$

where K_z is the vertical hydraulic conductivity and Δh is the hydraulic-head anomaly associated with dewatering the pit. Regional-scale bedrock anisotropy can exceed three orders of magnitude; a conservative estimate is one order of magnitude. The bulk hydraulic conductivity of the regional flow model adjusted for anisotropy gives $K_z \sim 0.2$ feet/day. The regional-scale flow model suggests a head anomaly of about 20 m due to dewatering. Bedrock effective porosity is poorly constrained, but $n_e \sim 0.05$

is a reasonable estimate. The depth to interface (D_i) is the idealized flow model (Fig. 1) is approximately two kilometers. This combination of parameters yields a groundwater flow rate (v) of a few meters per year and a corresponding time lag of several decades to a century. In this restrictive scenario, over the 20 years that the West Pit will be dewatered (the East Pit is dewatered for a shorter duration of time) it is unlikely that the underlying salinity structure reaches steady state. A less restrictive scenario in which the depth to interface is replaced by some representative depth to a mixing zone gives significantly reduced time lags. If the mixing zone is located within approximately two hundred meters of the pit bottom, it is physically plausible for the salinity structure to reach isostatic equilibrium and, as described in the previous section, for brackish groundwater to discharge to the mine while it is dewatered. Note that this analysis ignores the effects of buoyancy and consequently underestimates the time lag, i.e. brackish groundwater is anomalously dense and the vertical driving head gradient is reduced accordingly.

References

Barr Engineering Co., 1977, Water Management Plan and Preliminary Engineering Report accompanying NPDES Permit for Minnamax Basin Discharge.

Garven, G., 1995, Continental-Scale Groundwater Flow and Geologic Processes, Annual Review of Earth and Planetary Sciences, v. 23, p. 89-117, DOI: 10.1146/annurev.ea.23.050195.000513

Hanor, J.S., 1994, Origin of saline fluids in sedimentary basins: in Parnell, J., (ed.), Geofluids: Origin and migration of fluids in sedimentary basins: Geological Society of London Special Publication No. 78, p. 151-174.

Hanor, J.S., 1987, Origin and Migration of Subsurface Sedimentary Brines, SEPM Short Course, v. 21.

Johnson, R.C., Andrews, R.A., Nelson, W.S., Suszek, T., and Sikkila, K., 1995, Geology and Mineralization of the White Pine copper deposit: IGCP 336 Field Trip Guidebook, Duluth, MN, 20 p.

Kelly, W.C., Rye, R.O., and Livnat, A., 1986, Saline minewaters of the Keweenaw Peninsula, Northern Michigan: Their nature, origin, and relation to similar deep waters in Precambrian crystalline rocks of the Canadian Shield: American Journal of Science, v. 286, p. 281-308.

Minnamax Project, 1976, Environmental Services Group Report, Monthly Report: July 15 – August 15, 1976.

Morton, P., and Ameel, J., 1985, Saline waters as indicators of economic mineralization, Minnesota Department of Natural Resources Report 241-1.

Rouleau, A., Guha, J., Archambault, G., and Benlahcen, A., 2003, An Overview of the Hydrogeology of the Precambrian Basement in Quebec and Related Mining Problems. in Groundwater in Fractured Rocks, IAH, Prague, Czech Republic, Kransny-Hrkal-Bruthans (eds).

Swenson, J.B., Larson, P.C., Person, M., Crawford, P.L., and Ripley, E.M., 2002, Continental glaciation as a groundwater-impelling mechanism: Pleistocene flushing of deep brines in the Lake Superior basin, GS-24, Geological Association of Canada and Mineralogical Association of Canada Joint Annual Meeting, May 27 - 29, Saskatoon, Saskatchewan.