Appendix E

Groundwater Modeling of the Treated Water Infiltration System

(Appendices E-2 and E-3 of Application sent to MDEQ)

Analytical Model Calculations for the Treated Water Infiltration System

Foth & Van Dyke

Memorandum

January 11, 2006

TO: Kennecott Eagle Project Master File 04W018-10001.4

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RE: Eagle Project – Analytical Model Calculations for the Treated Water Infiltration System

Introduction

This memo summarizes the methods and results of analytical modeling of the groundwater mound from the planned treated water infiltration system (TWIS) at the Kennecott Eagle Minerals Company (KEMC) Eagle Project site. This work is meant to support the Basis of Design for the Groundwater Infiltration System. Additional modeling work to be included in the *Groundwater Discharge Permit Application* will further assess the impact of the infiltration system. The moundinganalysis presented here is intended to provide a basis for the layout of the infiltration system.

The goal for the design of the infiltration system is to provide ample distribution of the discharge water that will not result in a surface seep, and will allow for the installation of multiple cells that can be cycled to provide adequate load rest cycles per regulatory requirements.

Methods and Inputs

Several analytical solutions are available for assessing infiltration mounding. One common approach is documented in USEPA's Process Design Manual for Land Treatment of Municipal Wastewater (USEPA, 1981). This 1-dimensional flow balance solution is appropriate for applications where the infiltration system is close to a groundwater discharge (venting) point such as a gaining stream. For the Eagle Project the nearest downgradient groundwater discharge point is more than 4,500 ft away. As such, an analytical solution that considers the 2-dimensional lateral spreading of the mound away from the infiltration area is required for scoping analysis on the size of the infiltration system.

The analytical solution for the expected mound formed in an isotropic, unconfined aquifer by constant and uniform infiltration over a rectangular area is based on the Hantush (1967) solution, with approximations provided by Finnemore (1995). Details of the analytical solution are described in Attachment A.

The groundwater mound is sensitive to several sets of input parameters. The groups of input required for the model are infiltration system loading characteristics, aquifer properties, and surface water boundary conditions.

II. A. Infiltration System Loading Characteristics.

The maximum discharge flow Q for design purposes is estimated at 400 gpm which will exceed the design basis for the WWTP of 350 gpm and thus provides excess capacity relative to project needs. The infiltration rate is simply the discharge divided over the discharge area. The field measured infiltration rate is 62 ft/d (North Jackson Company, 2006). MDEQ requires that the design infiltration rate is limited to 3% of the field measured rate (approximately 1.5 ft/d in this case). At 400 gpm and a design infiltration rate of 1.5 ft/d, an infiltration area of 51,300 sq. ft or greater is required.

350 gpm = 504,000 gpd
400 gpm = 576,000 gpd

The design infiltration rate may be reduced in order to reduce the amount of mounding that occurs or to adjust the infiltration over a set area. For the purposes of this memo, two infiltration scenarios are identified and summarized in Table 1. Scenario 1 is set to the design infiltration rate of 1.5 ft/d and Scenario 2 is for a reduced infiltration rate thatwas selected to reduce the peak height of the infiltration mound and accommodate heterogeneous subsurface conditions.

Table 1
Infiltration Scenarios Considered for the Groundwater Infiltration System

Scenario	Discharge (gpm)	Infiltration Rate (ft/d)	Required Area of Infiltration System (sq ft)
1	400	1.5	51,300
2	400	0.50	154,000

Another input for the infiltration loading is the duration of loading, t. For this analysis, the duration of infiltration loading is assumed to be 1 year (365 days). This assumption is considered appropriate for several reasons. First, the design infiltration rate for the scenarios exceeds the WWTP design basis maximum of 350 gpm. Second, the maximum discharge from the WWTP will only occur for a period of several weeks to months during peak runoff events. Third, the average annual discharge to the system based on the water balance is significantly less than the 400 gpm considered in these scenarios. Fourth, calculations completed as part of this analysis indicated that the peak mound height based on a discharge of 400 gpm for 1 year was greater than the mound height based on the average discharge for an approximate seven year mine operating life.

II. B. Aquifer Properties.

There are three model parameters used to describe the relevant aquifer conditions, horizontal hydraulic conductivity (K), the initial saturated thickness of the aquifer (h_0), and the specific yield (Sy). The horizontal hydraulic conductivity in the A and D zones is reported as 61 ft/d and

55 ft/d, respectively (North Jackson, 2005). Recent aquifer testing near the proposed infiltration area indicates a horizontal hydraulic conductivity of approximately 25 ft/d at the location of the infiltration system (North Jackson Company, 2006). Accordingly, a horizontal hydraulic conductivity of 25 ft/d was selected as the model input for *K*. The specific yield of 0.15, common for sands, was selected. Mound results were also calculated using a specific yield of 0.05.

The initial saturated thickness of the aquifer varies, as is shown in the conceptual schematic in Figure 1. In the region of the infiltration system, the saturated thickness is within a general range of 10-30 ft. Further to the northeast, the saturated aquifer thickness decreases, then joins the D zone aquifer. With consideration of the aquifer thickness near the infiltration system, the transition of the A and D zone aquifers with a higher hydraulic gradient, and the groundwater seep to the northeast, a value of 25 ft was selected for the initial aquifer thickness. The sensitivity of these assumptions is evaluated in Section IV of this memorandum.

<u>II. C. Selection of Width and Length of Infiltration Area.</u>

The required infiltration areas for Scenario 1 and Scenario 2 are presented in Table 1. In general, the peak mound height is reduced when the length of the infiltration area is significantly greater than the width. The width of the infiltration area is usually oriented in the direction of groundwater flow. For the proposed KEMC infiltration area, the groundwater flow direction is to the northeast.

Since the area is set by the discharge flow and the infiltration rate, the width and length of the infiltration area can be set to achieve a desired aspect ratio. For Scenario 1, an aspect ratio of nearly 10 was selected (72 ft x 711 ft). For Scenario 2, the infiltration area is increased, and the aspect ratio was reduced to roughly 7 in order to control the length of the area within the general bounds of the KEMC processing site (150 ft x 1026 ft). = 153,900 ft²

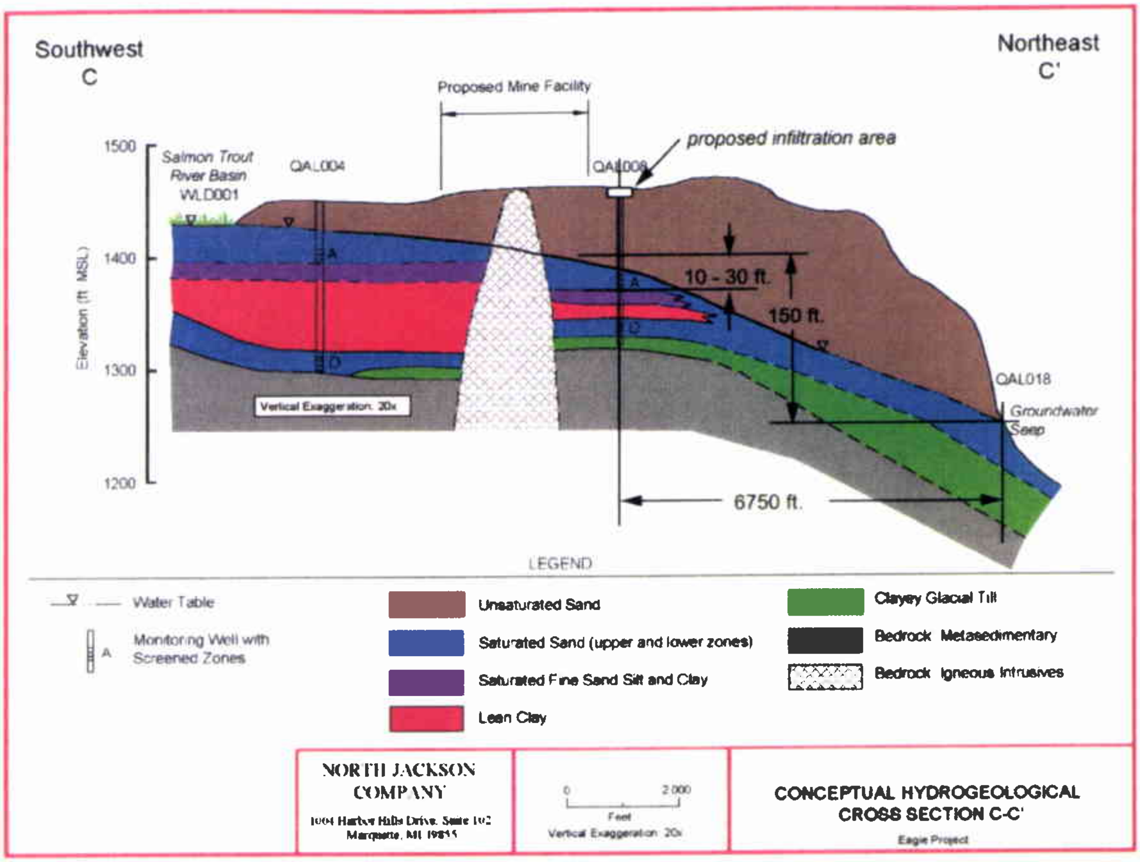

Figure 1. Hydrogeological Cross Section C-C' Provided by North Jackson Company, modified to show location of infiltration system, dimensions of saturated thickness of aquifer, and distance to groundwater seep.

Results

The mounding results will be discussed in terms of the maximum mound expected directly beneath the infiltration system for Scenario 1 and Scenario 2, the spatial distribution of the mound for Scenario 2, and results that show parameter sensitivity for Scenario 2. Scenario 2 is selected for more detailed analysis since its dimensions will reduce mounding, allow for adequate load rest cycles and accommodate heterogeneous subsurface conditions.

III. A. Maximum Mound Expected Directly Beneath Infiltration System.

The maximum mound thicknesses expected beneath the centroid of the infiltration system for two scenarios are shown in Table 2, and further details are shown in Table 3. The mound thickness is added to the initial saturated aquifer thickness (25 ft) to yield the expected saturated thickness. Scenario 1 has the highest infiltration rate and smallest area, and the mound thickness is greater than Scenario 2 by 3.7 ft.

While decreasing the infiltration rate has a relatively small impact on the peak mound height, the additional area for Scenario 2 will allow more operational flexibility, such as load/rest cycles in segmented cells.

Table 2
Maximum Mound Thickness Expected for Infiltration Scenarios

Scenario	Infiltration Rate (ft/d)	Width (ft)	Length (ft)	Area (Ac.)	Maximum Mound Thickness (ft)
1	1.5	72	711	1.2	33
2	0.50	150	1026	3.5	30

Notes:
Assumes 400 gpm input for 365 days, initial saturated thickness of 25 ft, horizontal hydraulic conductivity of 25 ft/d and specific yield of 0.15.

Table 3

Infiltration Mound and Input Details for

Infiltration Scenario 1 and Scenario 2

Maximum Mound Height above aquifer					
z_m =	**33.3 ft.**				
error =	0.0 <— Apply "Solver" (under "Tools" menu) so this is zero				
Infiltration Loading		**Infiltration Area**		**Aquifer**	
Flow rate, Q =	**400 gpm**	Width, W	**72.2 ft.**	Thickness of aquifer, max, h_m =	58.3 ft.
	77002 cu. ft./d	L (≥W)	711.0 ft.	Thickness of aquifer, initial, h_init =	**25 ft.**
Infiltration Rate, I =	**1.5 ft/d**	Area	51334 sq. ft.	Specific Yield, Sy =	**0.15**
			1.18 Ac.	Hyd. Conductivity, K =	**25 ft/d**
Duration, t =	**365 d**	r = L/W	9.85		

Scenario 1: 1.5 ft/d infiltration rate with W = 72 ft (22 m), L = 711 ft (217 m)

Maximum Mound Height above aquifer					
z_m =	**29.6 ft.**				
error =	0.0 <— Apply "Solver" (under "Tools" menu) so this is zero				
Infiltration Loading		**Infiltration Area**		**Aquifer**	
Flow rate, Q =	**400 gpm**	Width, W	**150.0 ft.**	Thickness of aquifer, max, h_m =	54.6 ft.
	77002 cu. ft./d	L (≥W)	1026.7 ft.	Thickness of aquifer, initial, h_init =	**25 ft.**
Infiltration Rate, I =	**0.5 ft/d**	Area	154003 sq. ft.	Specific Yield, Sy =	**0.15**
			3.54 Ac.	Hyd. Conductivity, K =	**25 ft/d**
Duration, t =	**365 d**	r = L/W	6.84		

Scenario 2: 0.5 ft/d infiltration rate with W = 150 ft (46 m), L = 1030 ft (313 m)

III. B. Spatial Distribution of Mound.

The spatial distribution of the mound expected from the infiltration system was calculated using input conditions from Scenario 2. A contour plot of the mound is shown in Figure 2. Since the mound solution is symmetrical with respect to the x-axis and y-axis, only one xy-quadrant of the infiltration area is plotted. The monitoring location coordinates (x,y) are described as distances from the center of the infiltration area, with the lateral distance along the length dimension (x-axis), and the normal distance along the width dimension (y-axis). Details of the mound along the width dimension are shown in Figure 3.

The mound thickness drops in an exponential fashion from the infiltration area, starting at 30 ft at the centroid of the infiltration area and dropping to 1 ft at 3000 ft, and to less than 0.1 ft at 5000 ft.

The expected infiltration mound can be added to the estimated groundwater elevations for Section C-C' to demonstrate the potential impacts to the regional flow. With the assumption that Section C-C' is oriented along the y-dimension of the calculated mound, the resulting approximated mound is shown in Figure 4. Most of the mounding is expressed in an area that appears to be unconstrained and well drained, with ample space for additional mounding in the unsaturated zone which is approximately 80-ft thick.

The initial saturated thickness of the A-zone aquifer in the infiltration area is roughly 10-30 ft. The Hantush solutions are suitable when the calculated mounding is generally less than 50% of the initial saturated thickness (Poeter, *et al*2005). The amount of mounding for the scenarios considered here exceeds this guideline. However, this is likely to result in an over estimation of mounding near the infiltration site and, therefore, additional modeling is warranted to check the solutions. However, the relatively high hydraulic conductivity and moderately high hydraulic gradient in the region of interest suggests that mounding is not likely to be excessive. In addition, the current estimates for the mound are based on several conservative assumptions and there is still ample space vertically and horizontally for additional mounding in the existing aquifer.

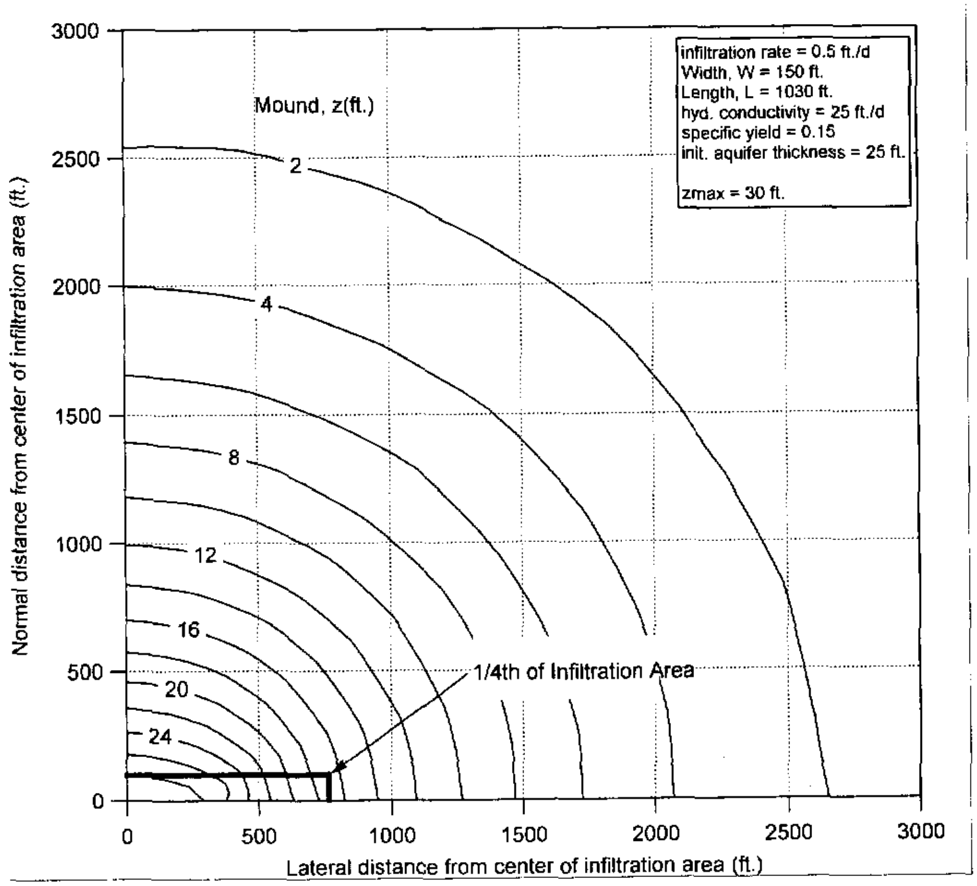

Figure 2 Spatial Distribution of Infiltration Mound for Input Scenario 2.

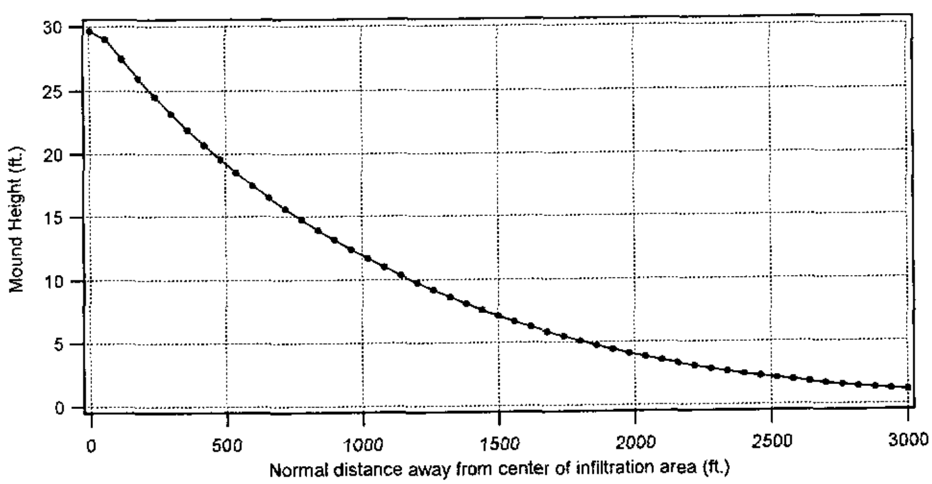

Figure 3 Detail of Infiltration Mound with Normal Distance (y-dimension) for Input Scenario 2.

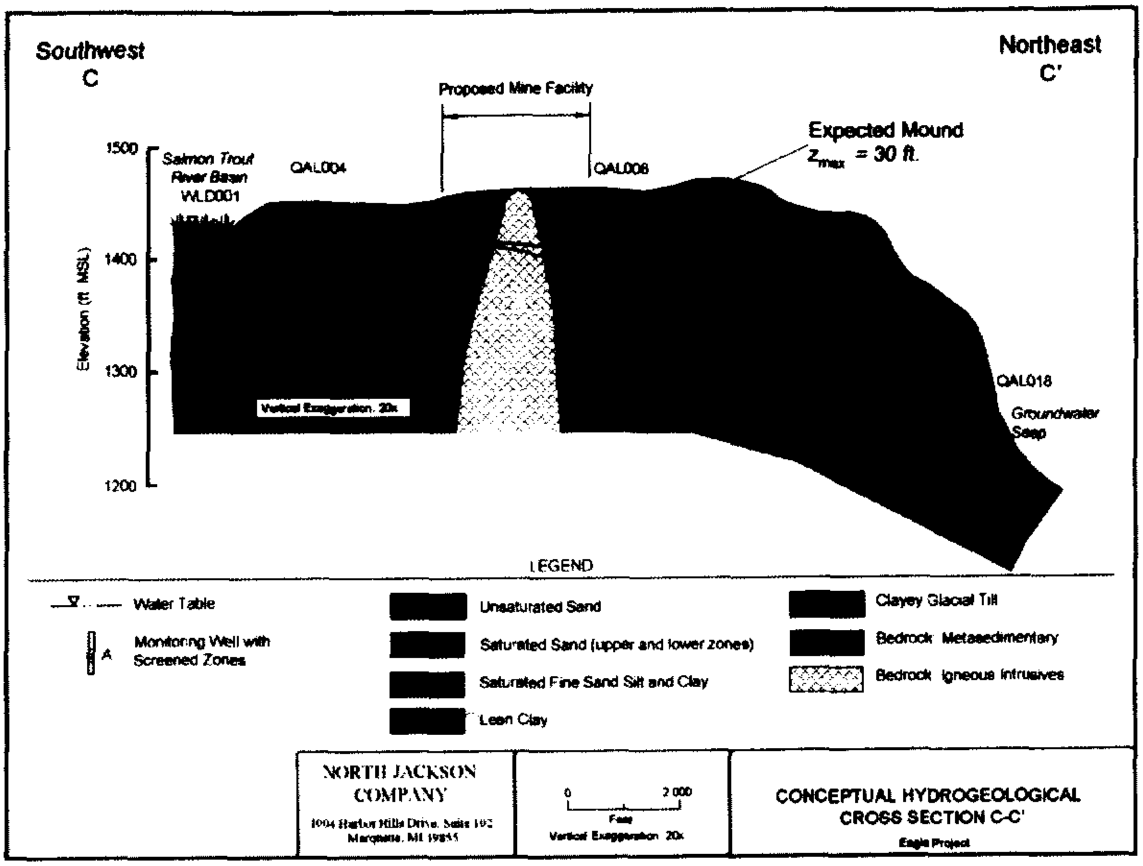

Figure 4 Expected Infiltration Mound for Scenario 2, Superimposed to Section C-C'. Section C-C' is along y-axis of mound geometry, and ignores potential effect of igneous intrusive bedrock on groundwater mound.

IV. Parameter Sensitivity

A set of alternate solutions were generated to demonstrate the general sensitivity of the solution to changes in the aquifer characteristics or loading conditions. The sensitivity of the parameters is discussed by comparisons of the mound heights, using Scenario 2 as the normal case. The effects of changes in hydraulic conductivity, initial saturated thickness, infiltration rate, and the specific yield were evaluated. A summary of the sensitivity study results is presented below.

A 50% decrease in hydraulic conductivity (K) causes the peak mound height to increase by roughly 50%, although a 100% increase in K caused only a 33% decrease in the mound height. Decreasing K also resulted in lower mound heights at distances greater than 1500 ft, whereas increasing K had a very small effect at distances of 1500 ft or greater.

The effect of increasing the initial saturated thickness (h_0) of the aquifer was to reduce the mound height, and vice versa. A 50% change in h_0 caused the peak mound height to change by roughly 15%. Effects at distances of 1500 ft or greater were very minor.

Although mounding is higher for cases with lower values of initial saturated thickness and hydraulic conductivity, Figure 4 shows that there is adequate vertical space to handle the mound.

The effect of changes in the infiltration rate (*I*) was also evaluated. A 50% decrease in *I* causes the peak mound height to decrease by roughly 40% for all distances. A 50% increase in *I* causes roughly a 33% increase in the peak mound height for all distances.

The effect of a reduction in the aquifer specific yield for Scenario 1 and Scenario 2 is shown in Figure 5. Decreasing the specific yield by a factor of 3 causes the mound height to increase by 5 ft. However, one may expect that the specific yield of the aquifer will generally increase with time due to saturation effects. An increase in the specific yield from 0.15 to 0.25 (not shown in Figure 5) causes the mound height to decreaseby 2.5 – 3.3 ft over all distances.

Summary

These sets of calculations of infiltration mound height show that, for the input conditions considered, the aquifer at the Eagle Project site has the capacity to absorb and transmit infiltrated treated water. There is ample vertical and horizontal space for the resultingmound. Results from this memo will be considered in addition modeling work to be included in the *Groundwater Discharge Permit Application.* These results also indicate no significant mounding impacts to surface waters or groundwater seeps, because the downgradient surface waters are more than 4,500 ft away from the infiltration area and the estimated mound height is negligible at those distances.

The larger infiltration area and reduced infiltration rate of Scenario 2 reduces the mound and will provide for adequate load rest cycles and accommodate heterogeneous subsurface conditions. As such the infiltration area dimensions of Scenario 2 are recommended for the basis of design of the infiltration system.

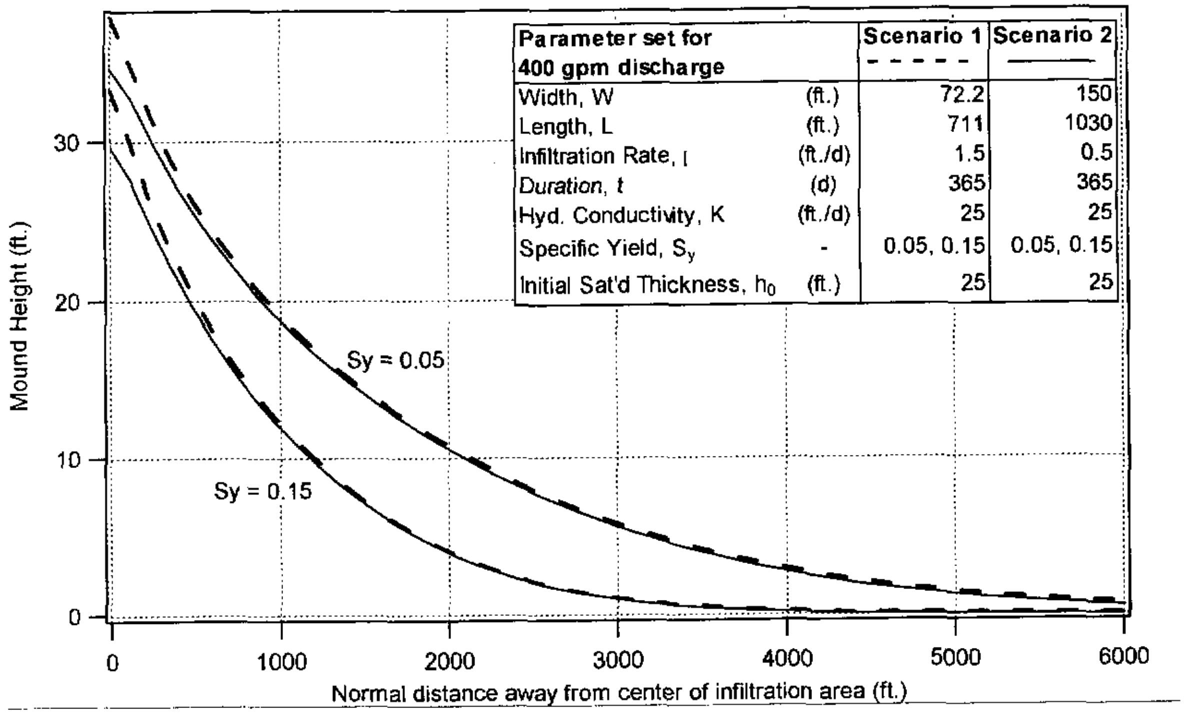

Figure 5 Effect of the Aquifer Specific Yield on the Infiltration Mound Calculated for Scenario 1 and Scenario 2.

References

Aish, A., and F. DeSmedt (2004), *Modeling of a Groundwater Mound Resulting From Artificial Recharge in the Gaza Strip, Palestine, Proceedings of the Second Israeli-Palestinian International Conference on Water for Life in the Middle East*, October 10-14, 2004, Turkey, 114-122.

USEPA (1981), *Process Design Manual, Land Treatment of Municipal Wastewater*. Chapter 5, EPA/625/1-81-013.

USEPA (2002), *Onsite Wastewater Treatment Systems Manual*. EPA/625/R-00/008. Office of Water, Office of Research and Development, US EPA, Cincinnati, OH.

Finnemore, E.J. (1995), *A Program to Calculate Ground-Water Mound Heights, Ground Water*, 33(1):139-143.

North Jackson Company (2005), *Kennecott Mineral Company Eagle Project Environmental Baseline Study, Interim Hydrology Report.*

Hantush, M.S. (1967), *Growth and Decay of Groundwater Mounds in Response to Uniform Percolation, Water Resources Research* 3(1):227 -234.

Poeter E., J. McCray, G. Thyne, and R. Siegrist (2005), *Guidance for Evaluation of Potential Groundwater Mounding Associated with Cluster and High-Density Wastewater Soil Absorption Systems*. Project No. WU-HT-02-45. Prepared for the National Decentralized Water Resources Capacity Development Project, Washington University, St. Louis, MO, by the International Groundwater Modeling Center, Colorado School of Mines, Golden, CO.

North Jackson Company (2006), *Supplemental Hydrogeologic Study for Groundwater Discharge*.

Attachment A

Groundwater mound from uniform and constant infiltration loading over rectangular area

Consider a rectangular infiltration area with length L and width W over an unconfined aquifer. The geometric conventions of the problem are shown in Figure A1. The maximum mound height, h_m, will be located under the centroid of the rectangle. Hantush (1967) provided an analytical solution for the mound height, which Finnemore (1995) conveniently expressed as an added mound height to the initial, saturated aquifer thickness, h_0,

$$z_{\max} = h_m - h_0 = \frac{I\,t\,S^*(\alpha,\beta)}{S_y} \tag{1}$$

where I is the uniform infiltration application rate (equal to the infiltration flow divided by the area), t is the duration of loading, S_y is the aquifer specific yield, and $S^*(\alpha, \beta)$ is defined as:

$$S^*(\alpha,\beta) = \int_0^1 erf\left(\frac{\alpha}{\tau}\right) erf\left(\frac{\beta}{\tau}\right) d\tau \tag{2}$$

where *erf()* is the error function. The non-dimensional variables, α and β, are defined as

$$\alpha = \frac{L}{4}\sqrt{\frac{S_y}{K\bar{h}t}} \tag{3}$$

$$\beta = \frac{W}{L}\alpha = \frac{\alpha}{r} \tag{4}$$

where K is the aquifer hydraulic conductivity, r is the aspect ratio of length to width, and $\bar{h}$ is the average of the mound height and the initial height:

$$\bar{h} = (h_m + h_0)/2 \tag{5}$$

Equation 2 is difficult to integrate, but Hantush (1967) offered an approximate solution for relatively small values of α and β, and Finnemore (1995) provided a more exact approximation. In this memorandum the Finnemore (1995) solution is incorporated intoa spreadsheet, along with a numerical integration method in a commercial scientific analysis and plotting software package (*IgorPro*[1], *v. 4.0*). Each solution requires an iterative procedure to solve for the mound height (because α and β are dependent on the mound height). The solutions have been cross-checked for accuracy. Aish and DeSmedt (2004) have shown good agreement between MODFLOW and the Finnemore approximations of the Hantush analytical solution.

Poeter, et al. (2005) notes that the Hantush Analytical Solution is considered accurate when the added mound is less than 50% of the initial saturated thickness of the aquifer ($z_{\max} < h_0/2$)

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[1] *IgorPro* is a trademark of WaveMetrics, Inc., Lake Oswego, Oregon.(www.wavemetrics.com).

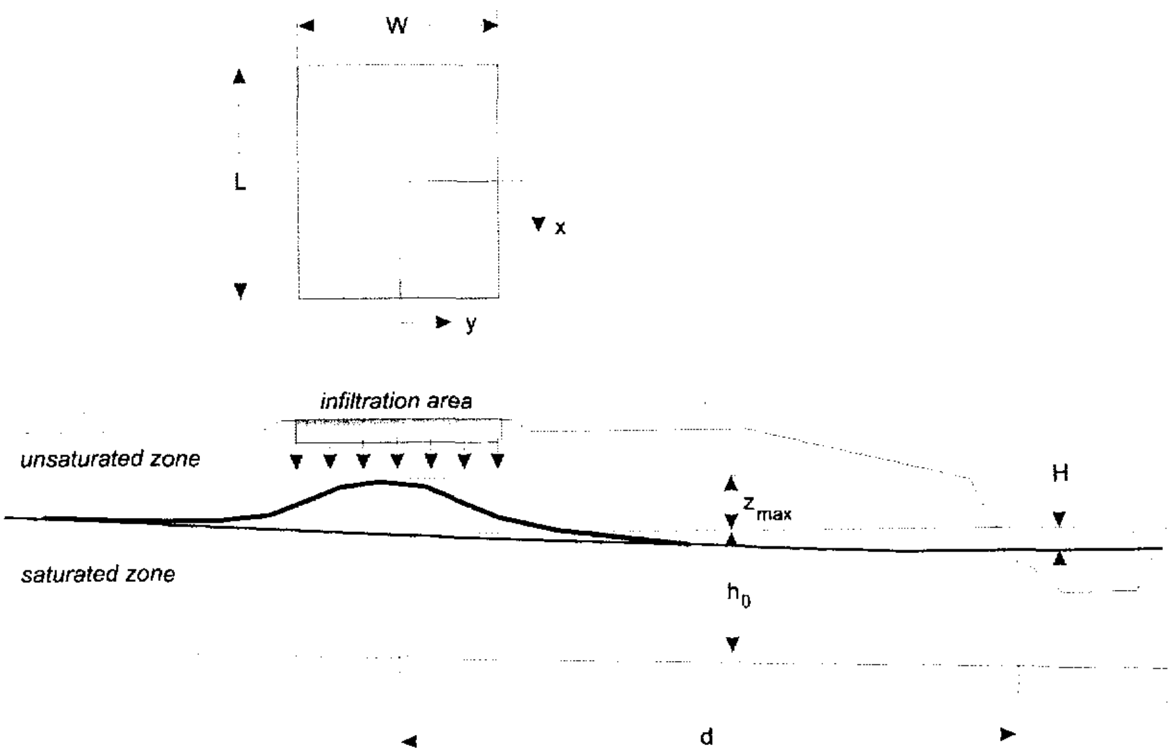

Figure A1. General geometric conventions for infiltration mound in unconfined aquifer.

Other factors, such as heterogeneous aquifers and complex boundary conditions typically require numerical modeling of the groundwater mound.

The solutions are consistent with the graphical solution method provided within the U.S. EPA Wastewater Treatment Systems Manuals (EPA 1981 and 2002). For cases for when subsurface discharge to a nearby surface water is expected, the EPA method uses an additional constraint to select a maximum width for the infiltration area,

$$W_{\max} = \frac{K\,h_0}{I}\left(\frac{H}{d}\right) \qquad (6)$$

where H is the initial difference in groundwater elevation and d is the lateral distance between the center of the infiltration area and nearby surface water. This equation balances the infiltration rate with the flow that would be expected (per unit length) in the aquifer unit. Agreement was excellent between the scanned and re-plotted EPA curves and the numerical evaluation, as is shown in Figure A2.

Although primary advantages of the EPA method are simplicity and wide-spread use, it is important to note that the EPA method has a few disadvantages. First, the method is graphical and potentially inaccurate, especially for small values of S* (Finnemore, 1995). Second, the method requires use of the maximum width for the infiltration mound. If a different width was

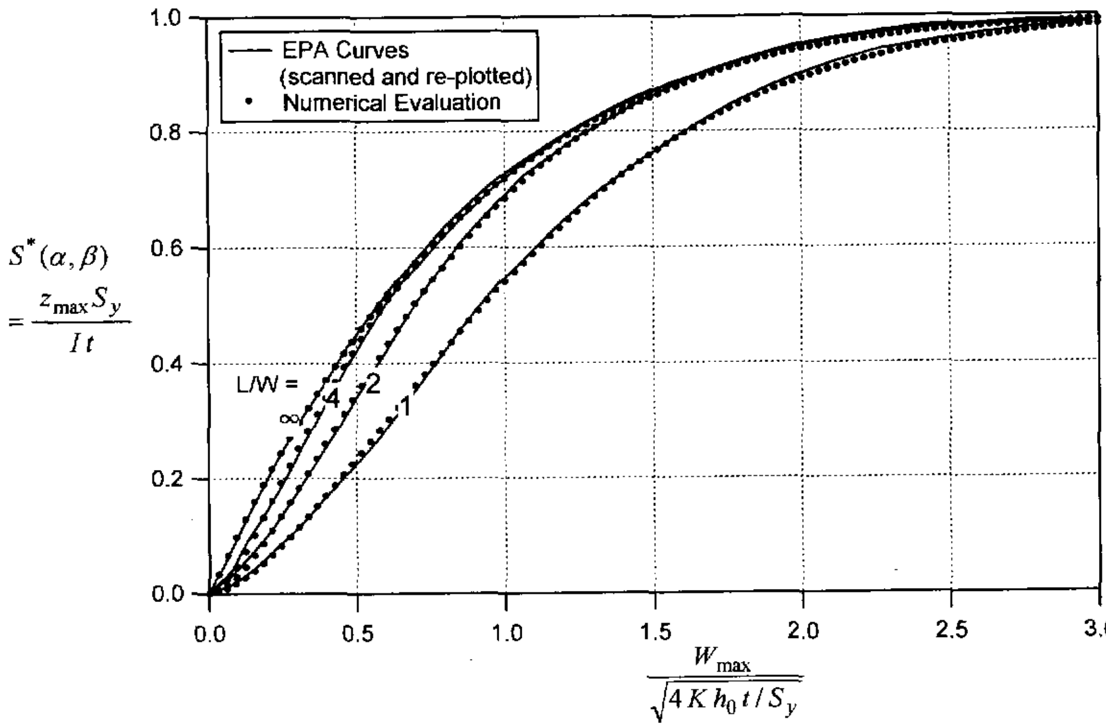

Figure A2. Agreement in published EPA infiltration mound curves (EPA 2002) with the numerical integration method described here.

used, the EPA method would require some modification in order to yield accurate estimates of the mound height. The EPA method does not account for situations where lateral spreading of the mound may be significant. In addition, the method is difficult to automate for multiple determinations. For these reasons, analytical approximations (Finnemore, 1995) and numerical integration are considered superior and should be used preferentially.

The numerical implementation in *IgorPro* has also been extended to predict and plot the mound heights over the full area of interest. The equation was provided by Poeter, *et al.*(2005), and has been adapted here to follow the solution conventions of Finnemore (1995) to a more convenient form:

$$\begin{aligned} z(x,y) &= h(x,y) - h_0 \\ &= \frac{It}{S_y}\left[S^*(\alpha_+,\beta_+) + S^*(\alpha_+,\beta_-) + S^*(\alpha_-,\beta_+) + S^*(\alpha_-,\beta_-)\right] \end{aligned} \tag{7}$$

where

$$\alpha_+ = \alpha\left(1 + \frac{x}{(L/2)}\right),\ \alpha_- = \alpha\left(1 - \frac{x}{(L/2)}\right),$$
$$\beta_+ = \beta\left(1 + \frac{y}{(W/2)}\right),\ \text{and}\ \beta_- = \beta\left(1 - \frac{y}{(W/2)}\right).$$

The monitoring location coordinates (x,y) are described as distances from the center of the infiltration area, with the x-distance being the direction of the length L, and the y-distance being along the width W (see Figure A1). Since the variables α and β are dependent on the mound height, a root-finding procedure is needed to solve for the mound height at each xy-coordinate. Because this was more difficult to implement in a spreadsheet, the solution was programmed in the numerical integration platform within *IgorPro*.

Groundwater Flow Model of the Treated Water Infiltration System

REPORT ON

GROUNDWATER MODELING OF INFILTRATION SYSTEM AT THE PROPOSED KENNECOTT EAGLE PROJECT, MICHIGAN

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1.0 INTRODUCTION

1.1 PROJECT BACKGROUND

Kennecott Eagle Minerals Company (Kennecott) is proposing an underground nickel and copper mine from an ore body located in the Yellow Dog Plains, approximately 9.5 miles southwest of Big Bay in Marquette County, Michigan (Figures 1 and 2). The project is formally called the Eagle Project.

1.2 STUDY OBJECTIVES

The Eagle Project will include a surficial infiltration system to recharge treated water. Kennecott is required to quantitatively assess the hydrologic affects of this system as part of the discharge permit application to the Michigan Department of Environmental Quality (DEQ). This report presents Golder Associates Inc. (Golder) groundwater modeling analysis of the planned treated water infiltration system (TWIS). This work was performed and the report has been prepared following the groundwater modeling guidelines included in the current version of the DEQ Manual (Michigan DEQ, 2002).

This work is intended to support the infiltration system design and Kennecott's permit application to operate the system at the project site. Previous analytical calculations were performed using different approaches and assumptions. This work conservatively estimates the hydrologic effect of operating the infiltration system on the local groundwater conditions. Of particular importance is the need to predict the magnitude and extent of groundwater mounding resulting from operating the proposed infiltration system.

1.3 ASSUMPTIONS

The infiltration assessment presented in this report is conservative with respect to mounding. The analysis is based on the assumption that a steady-state hydrologic condition is achieved instantaneously. In reality, the groundwater mound will develop over time as operation of the infiltration system continues. As such, the steady-state mound height predicted here may never actually be reached. Associated with this, the predicted infiltration water travel times are based on the same steady-state mound. The actual hydraulic gradient will increase with time as the mound develops. Prior to reaching steady-state, hydraulic gradients will be flatter than assumed in this modeling work. Therefore, the resulting travel times will be greater than predicted by the modeling analysis.

Existing available information was sufficient to formulate the groundwater model properties so that no additional investigation work was performed by Golder to support the analysis presented herein.

2.0 HYDROGEOLOGIC CHARACTERIZATION

2.1 PREVIOUS REPORTS

A significant amount of site investigation and characterization assessment work has been performed to date. No additional specific site characterization was performed to support the infiltration analysis documented in this report. The reports that document this effort, findings and interpretations that are most relevant to the analysis presented herein are summarized below. The reader is referred to these reports for detailed information. Figure 3 shows the location of the main features.

2.1.1 ENVIRONMENTAL BASELINE STUDY

- North Jackson Company. 2005a. Environmental Baseline Study, Hydrologic Report Volume 1, prepared for Kennecott Minerals Company and Golder Associates Inc. September, 2005.
- North Jackson Company. 2005b. Environmental Baseline Study, Hydrologic Report Volume II (Appendices), prepared for Kennecott Minerals Company and Golder Associates Inc. September, 2005.

These two documents provide an assessment of existing hydrologic conditions at and near the Project site. The reports include detailed information for the 15 soil borings, 20 monitoring wells and 27 hand-driven piezometers that were drilled and installed as part of the investigation. These details include well construction (casing type and screen interval) information, location coordinates, piezometric level data, hydraulic test results and water quality data.

2.1.2 SUPPLEMENTAL HYDROGEOLOGIC STUDY FOR GROUNDWATER DISCHARGE

- North Jackson Company. 2005c. Supplemental Hydrogeologic Study for Groundwater Discharge, Kennecott Minerals Company Eagle Project. January, 2006.

This report provides an updated description of environmental conditions, including results of additional monitoring well installation, hydrologic monitoring and infiltration testing, determination of the hydrostratigraphy, aquifer and aquitard properties, groundwater and surface water flow conditions, and the water budget. The report also includes a detailed conceptual understanding of the local groundwater flow system.

2.1.3 ANALYTICAL INFILTRATION CALCULATIONS FOR THE TWS

- Foth & Van Dyke. 2006. Technical Memorandum: Eagle Project - Analytical Model Calculations for the Treated Water Infiltration System, dated January 11, 2006.

This infiltration analysis was performed to establish a hydrogeologic basis for the layout of the infiltration system and to provide an initial estimate of the hydrologic effects (such as mounding and potential for surface seepage) of operating the system. The analysis was based on the assumption of an isotropic, unconfined aquifer of infinite lateral extent, with an initially horizontal water table (that is, no gradient). The infiltration was run for one year. Two infiltration distribution cases were assessed, resulting in maximum mounding at the site of between 29.6 and 33.3 feet, and a radial extent (defined by the 2-foot rise contour) of up to 3,000 feet.

2.2 HYDROLOGY

Most precipitation in the area occurs as rainfall between April and September and as snow between November and March. Average monthly precipitation ranges from 1.8 inches (in February) to 4 inches (in October), and the annual average was 35.59 inches between 1979 and 1998.

The major surface water features in the site area consist of the following:

- Yellow Dog River - which drains the Yellow Dog Plain to the south of the site,
- Salmon Trout River System – which drains the area to the west and east of the site, and deeply incises the Quaternary sediments
- Numerous streams that originate along the Terrace Slope at groundwater discharge points.

Detailed flow monitoring has occurred along the major streams and at several terrace seeps. The streamflow follow typical seasonal patterns with peak flows associated with snowmelt runoff and low flows in summer and winter.

The conceptual understanding of groundwater flow in the area consist of the Plains wetlands acting as a primary groundwater recharge and storage area supported by precipitation. The streams that originate along and drain the Terrace Slope north of the site act as the main groundwater discharge features.

2.3 GEOLOGY AND HYDROSTRATIGRAPHY

2.3.1 GEOLOGY

Figure 4 shows the generalized geologic profile north to south from the Yellow Dog Plain to Lake Superior. The profile includes the interpreted extent and thickness of the alluvial sediments beneath the Plain and the terrace slope, and the extent of the bedrock. Figure 5 shows the conceptual hydrogeologic conditions, including the general recharge and discharge areas, the unsaturated zone thickness.

The local bedrock consists of metasedimentary rocks of the Michigamme Formation, which is part of the Precambrian-age Marquette Range Supergroup. Lithologically, these rocks consist of fine-grained clastic rocks such as black slate and siltstone. The Michigamme Formation is flanked to the north, south and east by older Archean gneissic basement rocks. Whereas Quaternary deposits cover the Michigamme Formation in the project area, the older rocks are exposed both to the north and south of the site.

The Quaternary deposits overlying the bedrock basement consist of outwash and till deposited during late-continental glaciation. The outwash sediments were deposited from glacial melt water and mostly consist of well-sorted, stratified sand and gravel. The till material was deposited by glacial ice, and is a poorly-sorted, non-stratified mixture of sand, silt, clay, gravel and boulders. The total thickness of the Quaternary deposit in the project area ranges up to 225 feet. Several hydrostratigraphic units have been recognized within the Quaternary deposit.

2.3.2 HYDROGEOLOGY

The primary hydrogeologic units of concern at the infiltration site are summarized as follows:

- A Zone - outwash and beach deposit. Comprised of well-sorted, fine-medium sand with some gravel. The unsaturated portion of this unit ranges from less than 5 feet beneath the wetlands to up to 100 feet beneath the Plain. The soils have a very high infiltration rate (approximately 30 inches per hour).
- B Zone - transition zone. Consists of a mix of sand, silt and clay also derived from glacial meltwater, but have a notably lower permeability than the A zone.
- C Zone - lacustrine deposit. Consists of a massive clay deposit ranging up to 73 feet thick
- D Zone - outwash till deposit. Comprises fine-medium sand with a higher heterogeneity than the A Zone material. Groundwater in this unit is mostly confined.
- E Zone - basal till. Consists of a poorly-sorted mix of sand- to boulder-sized clasts in a fine grained matrix.

Figure 6 illustrates the interpreted unsaturated zone isopachs in the project area. This thickness ranges from about 20 feet near the Salmon Trout River to the west of the site to more than 120 feet in the area northeast of the infiltration site. The unsaturated zone thickness beneath the infiltration site is between 70 and 110 feet.

The two main aquifers beneath the site are the A and D Zones which are mostly separated by the lower permeability B and C Zones which essentially act as a confining unit. Figure 7 shows the interpreted thickness of the B and C zone units and is between zero and 20 feet at the site. The confining unit has a maximum thickness of more than 100 feet beneath the Yellow Dog Plain wetlands but pinches out beneath the Terrace Slope.

Soil boring details and results of material property testing are included in the previous investigation reports summarized in Section 2.1 above.

2.4 GROUNDWATER LEVELS AND FLOW

Figures 8 and 9 show the interpreted potentiometric levels in the A and D Zones, respectively, during May 2005. Groundwater levels are typically at a seasonal high in May as recharge is mostly springtime snow melt. The hydraulic gradients in the A and D Zones near the site were approximately 0.014 ft/ft and 0.016 ft/ft, respectively with groundwater flowing to the <u>northwest in</u> both zones. NE!

Figures 10 and 11 show groundwater hydrographs for eight of the nested monitoring wells at the site between May 2004 and August 2005. The water levels in these wells fluctuated by between one and 5 feet during this period. The water levels in the A and D Zones differed by up to 35 feet in well QAL008 (which is located close to the proposed infiltration site) and by less than 2 feet in well QAL005 (located upgradient from the site). In contrast, the deeper D Zone levels in wells QAL004 and QAL007 were consistently higher than those in the shallower A Zone, indicating an upwards hydraulic gradient. The vertical hydraulic gradient at the other wells was downwards.

Tables of monitoring well and piezometer construction details, and measured water levels are included in the previous investigation reports summarized in Section 2.1 above.

3.0 GROUNDWATER MODEL CONCEPTULIZATION

3.1 OVERVIEW

The primary focus during model construction was to develop a tool that could provide reasonably accurate estimates of the hydrologic effects resulting from the proposed infiltration. This involved creating a groundwater flow model and using an advective transport program to predict the fate of the infiltrated water. The site investigations performed to date indicated that the hydrogeologic conditions are relatively complex. However, the objective of this modeling effort was to represent the principal components of the system in a uniform manner, rather than including detailed features and then employ reasonably conservative assumptions to predict the long-term effects of infiltration..

3.2 MODELING CODE AND SOFTWARE

Golder selected the USGS' finite-difference code *MODFLOW-96* (Harbaugh and MacDonald, 1996) to simulate the groundwater flow field and the associated program *MODPATH* (Pollock, 1994) to perform advective particle tracking.

The commercial software program *GMS* (version 3.1; BYU-EMRL, 2000) was used to create, run and view the model. The GMS program includes a graphical user interface and several analysis codes (including *MODFLOW* and *MODPATH*).

3.3 MODEL DOMAIN

The model domain occupies an area of 21,500 feet by 16,000 feet in plan view (Figure 12). The process of finalizing the model area was an iterative one, with several versions tested before the actual area was selected. The model area is roughly centered on the planned infiltration site. The domain is subdivided uniformly into discrete cells, each with plan dimensions of 100 feet by 100 feet (for a total of 215 columns by 160 rows; Figure 13), and into three layers of variable thickness.

3.4 LAYERING AND UNITS

The top surface of the model varied from an elevation of 1,460 feet msl (in the southwest on Yellow Dog Plain) to 1,280 feet msl (at the base of the Terrace Slope) (Figure 14). The model base varied from 1,300 feet msl in the southwest to 1,200 feet msl in the northeast. The uppermost layer mostly represented the A Zone unit, the middle layer represented the combined B and C Zones, and the lowest layer represented the D Zone unit. The model base surface was deemed to coincide with the top of the underlying till and bedrock units. For this analysis, the bedrock outcrop located near the site is not included. Although layer 2 is dedicated mostly to the relatively impermeable B and C Zones, it also represents the D Zone north of the point at which the B and C Zone pinch out.

3.5 PROPERTIES

The following properties were assigned to the model layers and units:

TABLE 1

Summary of Modeled Properties

Model Layer	Hydrologic Unit(s) (Zone)	Horizontal Hydraulic Conductivity (Kh) *(ft/day)*	Vertical Hydraulic Conductivity (Kv) *(ft/day)*	Specific Storage (Ss) *(ft^{-1})*	Specific Yield (Sy) *(-)*	Effective Porosity (n_e) *(-)*
1	A	30	3	5e-6	0.05	0.15
2*	B/C	1	0.1	5e-7	0.01	0.15
3	D	25	2.5	5e-6	0.05	0.15

Note: * - Layer 2 to the northeast of the B/C unit extent uses Zone D properties.

3.6 BOUNDARY CONDITIONS

The upgradient and downgradient model boundaries were simulated using constant heads of 1,450 and 1,255 ft msl, respectively. These boundaries allowed groundwater to enter and leave the model. As such, no direct application of natural recharge was assigned as this water source was deemed to be implicitly included in the inflow boundary. The other model boundaries were set as no flow type and were deemed to be parallel to ambient groundwater flow direction. As mentioned above, these model boundary limits were iteratively determined to avoid the infiltration response being artificially affected. No other internal sources or sinks (such as rivers or springs) were included in this model. In reality, numerous surface water features exist that influence groundwater flow and discharge.

3.7 BASELINE GROUNDWATER FLOW FIELD

Figures 14 and 15 show the baseline groundwater flow field in plan and section views, respectively. The hydraulic gradient is relatively flat across the Yellow Dog Plain from the SE boundary to the edge of the Terrace Slope (approximately 0.01 ft/ft) but increases beneath the Terrace Slope (approximately 0.015 ft/ft). The model simulates an unsaturated zone depth beneath the site of approximately 75 feet, which is towards the low end of the measured thickness range of 70 to 110 feet (see Figure 6). The water table beneath the Terrace Slope is much shallower and intercepts the land surface at the base of the slope.

The baseline flow field was intended to generally match current conditions described in the hydrogeologic study. Groundwater levels are reasonably similar to those recorded at the monitoring wells and piezometers in the site area. For example, the modeled groundwater level at QAL008A (located close to the infiltration site) is approximately 1,391 ft msl; the water level measured in this monitoring well during 2004 and 2005 ranged from 1,389.3 to 1,390.4 ft msl.

As a result of the simplifying assumptions incorporated into the model, the model did not reproduce the downward vertical hydraulic gradients that were observed in the nested piezometers (see Section 2.4; Figure 10 and 11) at the infiltration site and only minor groundwater flow occurs through the B and C units (layer 2) in the model. The absence of downward hydraulic gradients in the model is a "conservative" factor in terms of predicting the extent and magnitude of groundwater mounding due to infiltration. This is because the model will over-predict groundwater mounding (higher than actual groundwater levels) as the natural conditions will result in some groundwater flow to the deeper units (B and C) thus resulting in a lower groundwater mound than predicted.

4.0 PREDICTIVE SIMULATIONS

4.1 INFILTRATION RATE

The infiltration of 400 gpm (77,000 cfd) of treated water was simulated using MODFLOW'S *Recharge* package, which added this flux directly to the water table in the uppermost layer in an area covering 1,000 feet by 150 ft (150,000 sq. ft). This equates to an applied rate of 0.5 ft/day. In reality, the areal extent of the recharge water at the water table would be expected to be slightly larger than 150,000 sq.ft due to lateral spreading within the unsaturated zone. However, the assumption of no lateral spreading is conservative for assessing the maximum mounding height.

4.2 MOUNDING

The model was run to steady-state and a new groundwater flow pattern was generated reflecting the infiltration of treated water (Figures 17 and 18). The groundwater flow pattern is similar to existing conditions, and the principal flow direction remains toward the northeast. Figure 19 shows the calculated, steady-state water table increase (mounding); the maximum increase is approximately 18 feet, decreasing radially from the site. This water table increase results in an unsaturated zone thickness reduction from 75 to 57 feet below the infiltration site. As the land surface near the site is relatively flat, this increase will not result in nearby surface seepage.

The approximate 2-foot groundwater mounding contour is between 3,500 and 7,500 feet from the site. The model results indicate that the mound will have an elliptical shape (rather than a truly radial shape) as a result of the ambient water table slope.

4.3 PARTICLE TRACKING

Golder used the particle tracking code *MODPATH* (Pollock, 1994) to determine the pathlines for the infiltration water upon reaching the water table. This involved adding a set of particles to the model at the center of the model cells receiving the infiltrated water, and allowing the particle to migrate conservatively (that is, without retardation due to sorption or other geochemical processes) in the steady-state flow field for up to 5 years. A time step increment of 30 days was employed to provide the necessary accuracy.

Figure 20 shows the resulting pathlines with map symbols indicating the location of the water particle after each year of travel. The results indicate that the infiltration water migrates to the northeast, despite some initial radial flow from the infiltration area. Many of the water particles are expected to reach the initial line of streams and springs that emanate on the Terrace Slope after about 4 years; some of these features (which are not represented in the model) are likely to act as discharge points for the water. The infiltrated water is predicted to reach the point close to piezometer QAL018 (a distance of 6,500 feet) after about 6 years.

5.0 MODEL SENSITIVITY AND LIMITATIONS

Although the model developed for this analysis represents the key aspects of the groundwater flow environment at and near the site, it includes several simplifying assumptions that should be considered when assessing the output results. These most notable assumptions are as follows:

- The model uses uniform aquifer properties and a generally uniform hydrostratigraphy;
- The model does not include numerous surface water discharge features; and
- The model uses no-flow and constant head boundary conditions that approximate current groundwater flow directions set sufficiently far from the infiltration area.

In reality, the units have variable transmissive properties (as evidenced by the range of hydraulic conductivities obtained from field testing), units are interrupted (such as where bedrock outcrops near the site) and have variable thickness. Several variations of the model described in previous sections were run in which the hydraulic properties and layer configuration were adjusted to assess the model's sensitivity in predicting mounding. For example, increasing only the hydraulic conductivity of the layers representing the A and D zones to 50 and 40 ft/day, respectively resulted in maximum mounding at the site of 14 feet, which is 4 feet less than for the original model. The radial effect of the infiltration was less widespread, with the 2-foot rise contour extending as far as 2,500 feet upgradient and 6,000 feet downgradient (Figure 21). Also, the travel time for the infiltrated water to reach the streams on the Terrace Slope was about 2 years (Figure 22).

The seeps, and to a lesser extent, the streams, that emanate from the Terrace Slope are fed by shallow groundwater. The seeps are located between 4,000 and 6,000 feet from the infiltration site. In practice, it is likely that some of the infiltrated water will discharge at these features before traveling the distances predicted by the model. This would reduce the down-gradient distance of the mound. However, due to their distance from the infiltration site, the Terrace Slope springs and seeps are not expected to have a significant effect on the groundwater table mounding at the site.

A sensitivity run was also performed for the particle tracking using a lower effective porosity value for the A and D zone units (10 percent) with the other hydraulic properties unchanged from those presented in Table 1. The results indicated that the water particles would migrate more rapidly than if a higher effective porosity is used, and that they would reach the edge of the Terrace Slope after about 3.5 years and piezometer QAL018 after about 5 years.

6.0 CONCLUSIONS

Golder developed a simple numerical model to simulate groundwater flow in the subsurface beneath the planned Eagle Project site to predict the mounding effects of infiltrating treated wastewater. The model estimates that recharging 400 gpm would cause the local groundwater table to rise by as much as 18 feet below the infiltration area. Therefore, the resulting depth to groundwater beneath the site would be approximately 57 feet.

The infiltration operation would also cause the water table to rise by 2 feet at a distance of between 3,500 and 7,500 feet from the infiltration area. The shape of the mound is predicted to be elliptical due to the effects of the ambient groundwater gradient and the dip of the aquifer unit beneath the Terrace Slope.

The particle tracking analysis indicates that the infiltrated water will migrate to the northwest. The water will migrate a lateral distance of between 400 and 500 feet in a one-year time period, and between 4,000 and 4,500 feet in 5-years. NE

Based on the available information, no public water supply wells are located within the model area. The predicted upgradient extent of the mounding is not expected to affect the surface hydrology of the Yellow Dog Plain.

The analysis is conservative in terms of predicting mounding and infiltration travel times as the model simulations assumed that steady-state conditions are attained. In reality, the groundwater mound will develop over time and mound height predicted here may never actually be reached. Also, the predicted infiltration water travel times were based on the same steady-state mound. The actual hydraulic gradient will increase with time as the mound develops. Prior to reaching steady-state, hydraulic gradients will be flatter than assumed in this modeling work and the resulting travel distances will be less than predicted by the modeling analysis..

7.0 REFERENCES

BYU-EMDS. 2000. GMS - Groundwater Modeling System. Version 3.1.

Foth & Van Dyke. 2006. Technical Memorandum: Eagle Project - Analytical Model Calculations for the Treated Water Infiltration System, dated January 11, 2006.

Harbaugh, A.W., and McDonald, M.G. 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

McDonald, M.G. and A.W. Harbaugh, 1988. A Modular Three-dimensional Finite-difference Groundwater Flow Model. U.S. Geological Survey Open-File Report 83-875.

Michigan Dept. of Environmental Quality. 2002. Groundwater Modeling Guidelines. Draft 1.0. October 16, 2002.

North Jackson Company. 2005a. Environmental Baseline Study, Hydrologic Report Volume I, prepared for Kennecott Minerals Company and Golder Associates Inc. September, 2005.

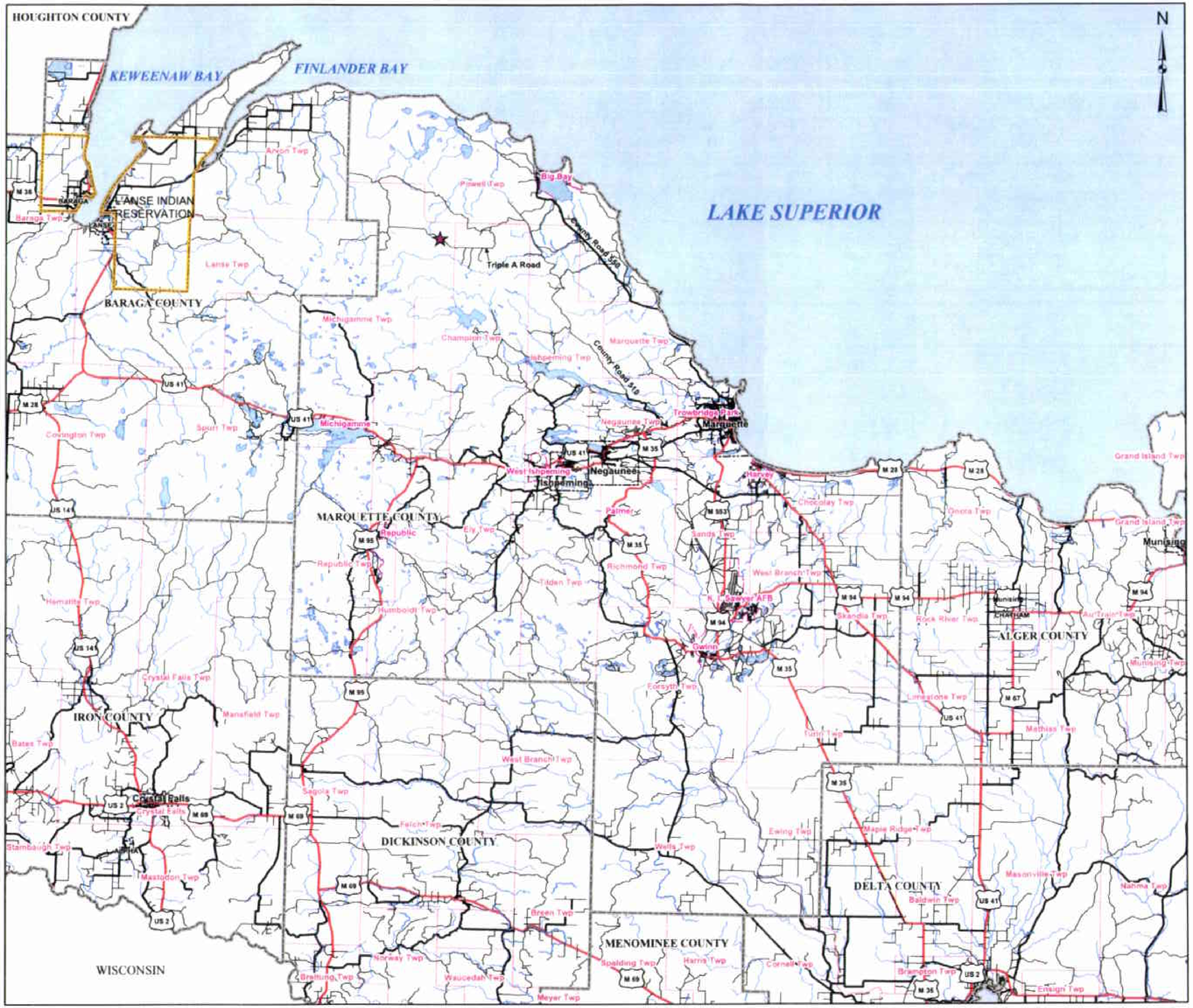
North Jackson Company. 2005b. Environmental Baseline Study, Hydrologic Report Volume II (Appendices), prepared for Kennecott Minerals Company and Golder Associates. September, 2005.

North Jackson Company. 2005c. Supplemental Hydrogeologic Study for Groundwater Discharge, Kennecott Minerals Company Eagle Project. January, 2006.

Pollock, D.W. 1994. User's Guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 6 ch.

FIGURES

FIGURES



LEGEND

- PROPOSED EAGLE PROJECT
- US HIGHWAY
- COUNTY ROAD
- MINOR ROAD
- AIRPORT
- HYDROGRAPHY
- MUNICIPAL BOUNDARY
- CENSUS DESIGNATED PLACE
- TOWNSHIP
- COUNTY
- INDIAN RESERVATION

REFERENCE

Digital data provided by Michigan Center for Geographic Information (CGI) (http://www.michigan.gov/cgi) and ESRI.
Datum: NAD 83 Projection: Michigan GeoRef (Meters)

10 5 0 10
SCALE 1:500,000 MILES

PROJECT
Kennecott Minerals

EAGLE PROJECT
BASELINE ENVIRONMENTAL STUDY
KENNECOTT MINERALS COMPANY

TITLE
SITE LOCATION MAP

Golder Associates

PROJECT No. 033-2156C			SCALE: 1:500,000	REV. 0
DESIGN	KG	19 Aug. 2004		
GIS	CHW	29 Jun. 2004		
CHECK	KG	24 Aug. 2004		
REVIEW	JM	25 Aug. 2004		

FIGURE: 1

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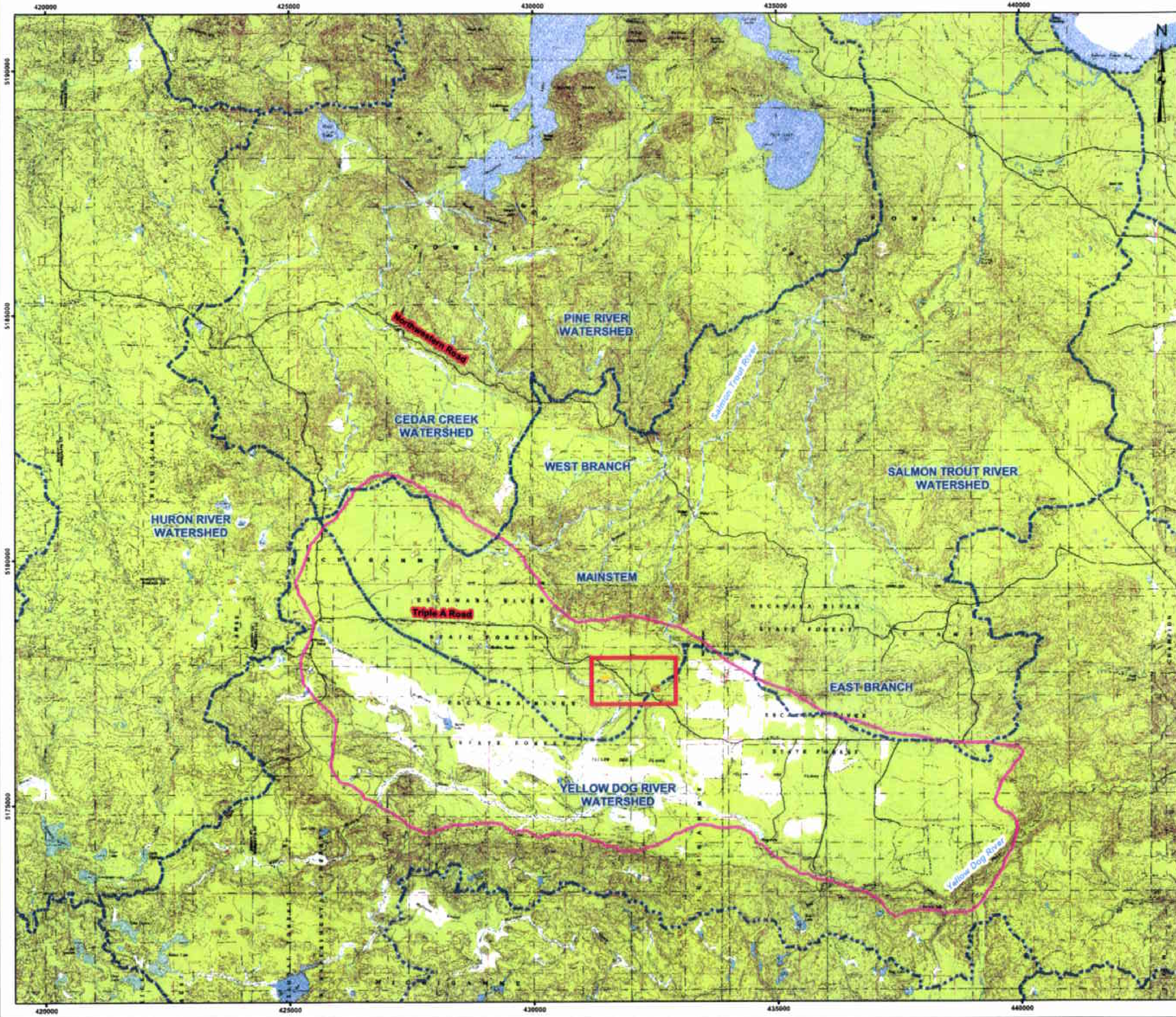

LEGEND

- STATE DEFINED SURFACE WATERSHED BOUNDARY
- PRELIMINARY SURFACE SUB-WATERSHED BOUNDARY
- ORE BODY
- OUTCROP
- EAGLE PROJECT
- YELLOW DOG PLAINS

REFERENCE

DRG and quaternary geology provided by Michigan DNR. Sub-watersheds delineated by Golder Associates Ltd. from Michigan DNR digital elevation model. Watersheds provided by Michigan DNR.
Datum: NAD 83 Projection: Transverse Mercator Coordinate System: UTM Zone 16

1 0 1
SCALE: 1: 80,000 MILE

PROJECT
Kennecott Minerals

EAGLE PROJECT
BASELINE ENVIRONMENTAL STUDY
KENNECOTT MINERALS COMPANY

TITLE

REGIONAL OVERVIEW

Golder Associates

PROJECT No. 033-2156C			SCALE AS SHOWN	REV. 0
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GIS	CHW	29 Jun. 2005		
CHECK	JM	27 May 2005		
REVIEW				

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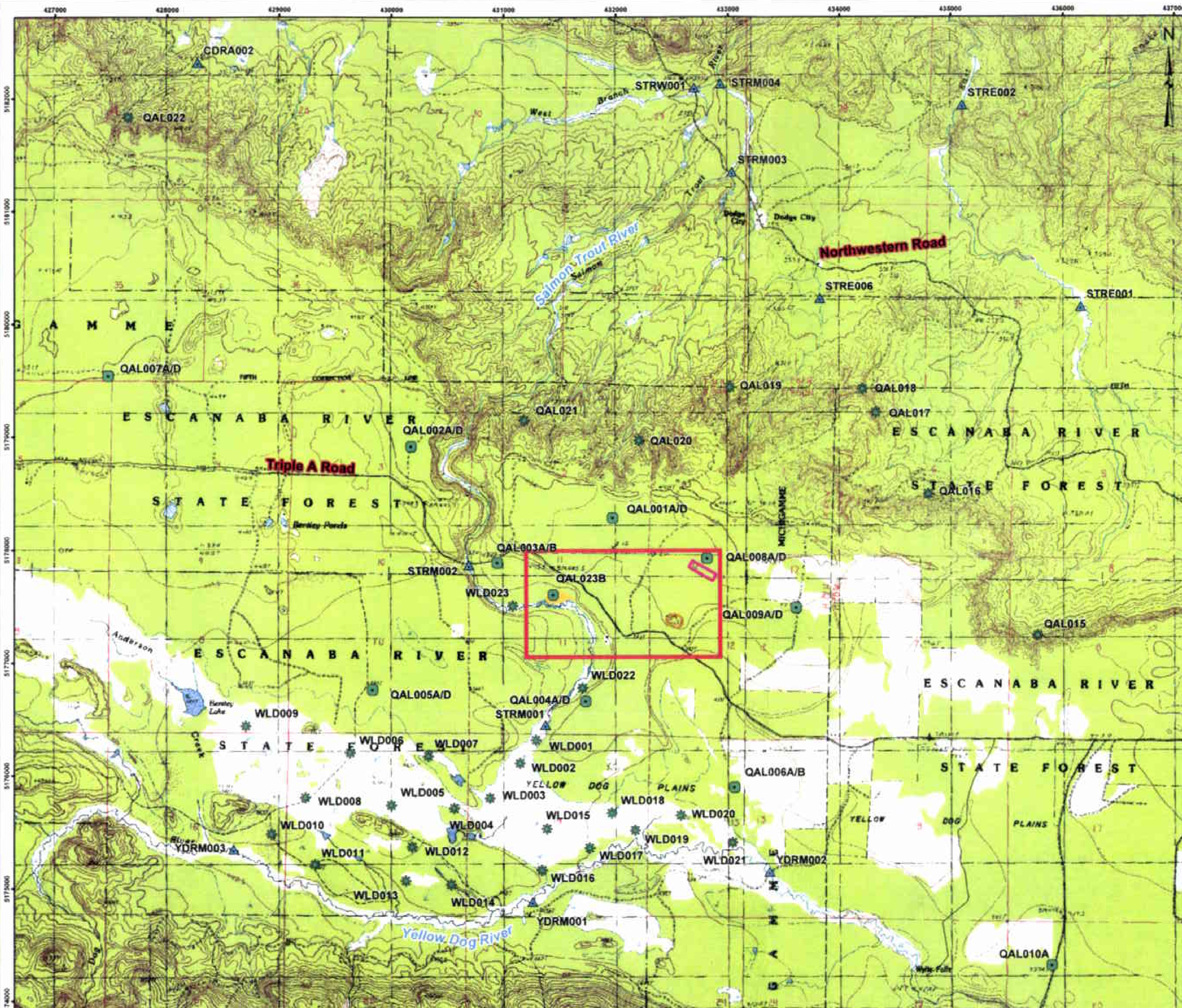

LEGEND

- ORE BODY
- OUTCROP
- EAGLE PROJECT
- INFILTRATION SITE
- MONITORING WELL
- PIEZOMETER
- SELECT SURFACE WATER MONITORING LOCATIONS

REFERENCE

DRG provided by Michigan DNR. Monitoring locations and cross-sections from North Jackson Company.
Datum: NAD 83 Projection: Transverse Mercator Coordinate System: UTM Zone 16

3,000 0 3,000

SCALE 1:35,000 FEET

PROJECT

Kennecott Minerals

EAGLE PROJECT
BASELINE ENVIRONMENTAL STUDY
KENNECOTT MINERALS COMPANY

TITLE

GROUNDWATER MONITORING LOCATIONS

Golder Associates

PROJECT No. 033-2156C			SCALE AS SHOWN	REV. 0
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GIS	TN	12 Apr. 2008		
CHECK				
REVIEW				

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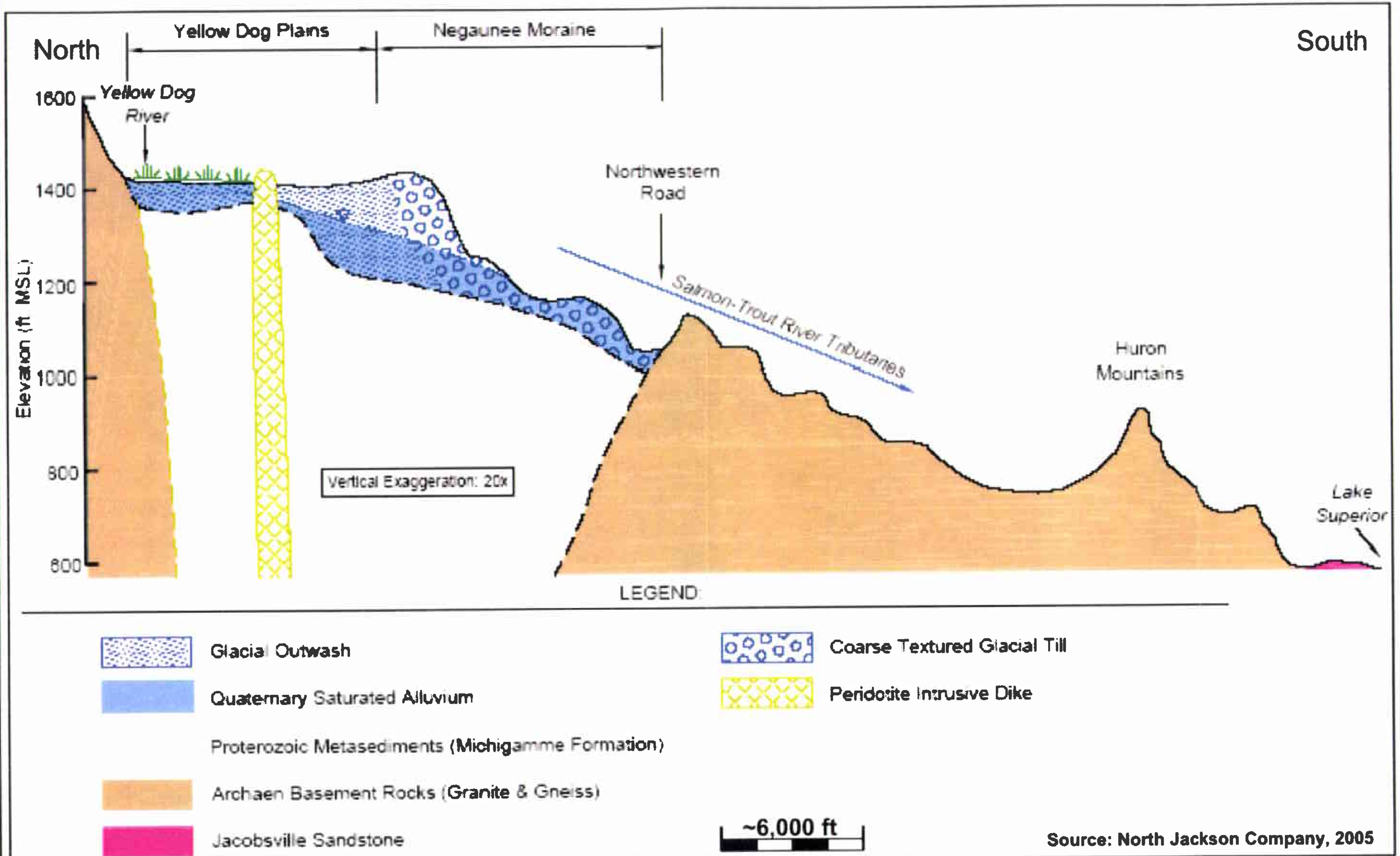

Golder Associates

Kennecott Minerals

Eagle Project – Groundwater Modeling of Proposed Treated Water Infiltration

TITLE

Generalized Geologic Section

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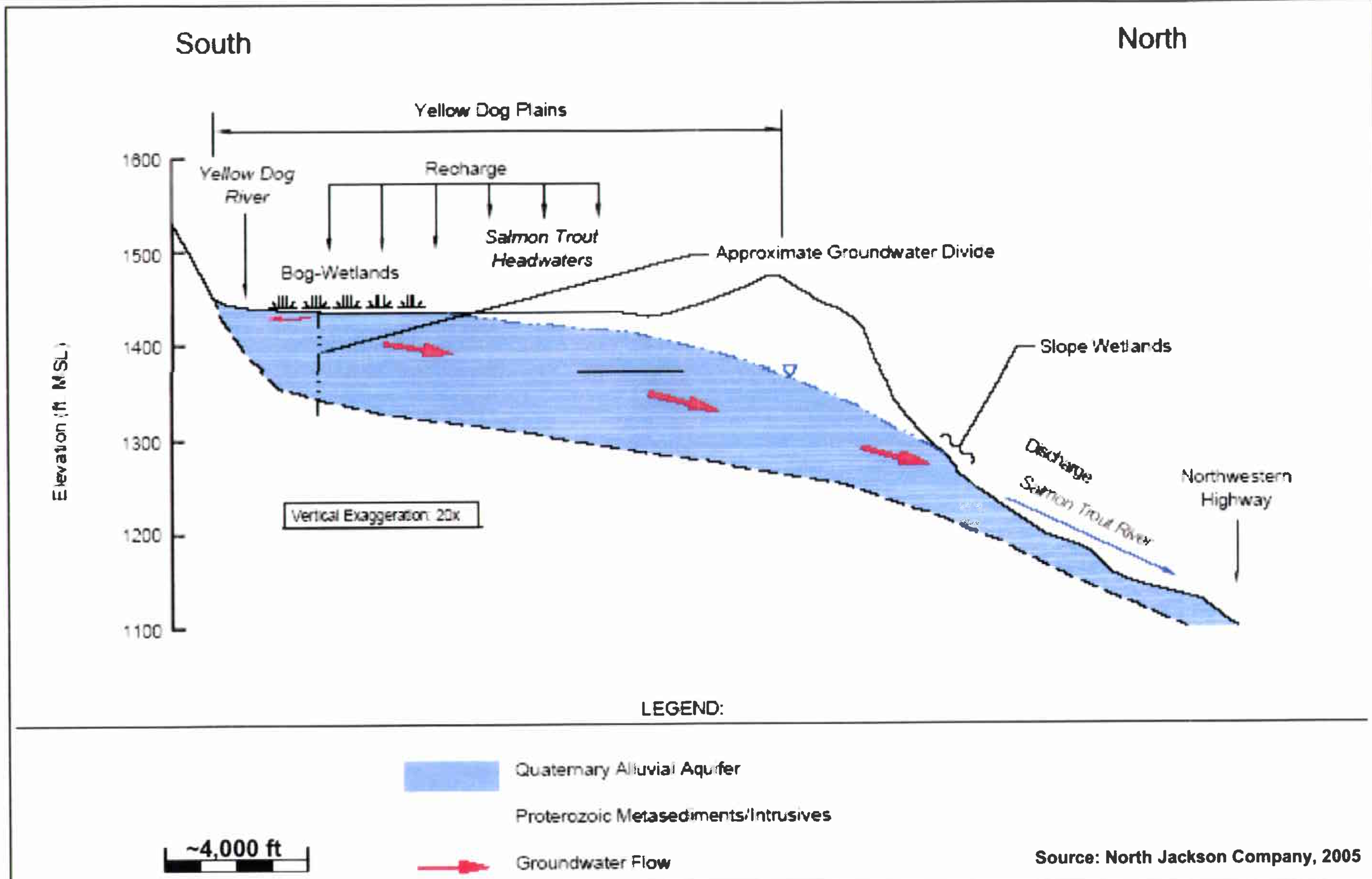
REVIEWED	DB	FILE No.	Kenn_model.pdf	FIGURE No.	4



Golder Associates

Kennecott Minerals

TITLE

Conceptual Hydrogeologic Section

Eagle Project – Groundwater Modeling of Proposed Treated Water Infiltration

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CHECKED	DB	SCALE		DWG No.	
REVIEWED	DB	FILE No.	Kenn_model.pdf	FIGURE No.	5