Class V Treated Water Infiltration System Application Review

Prepared for:

Mr. Jeffrey McDonald
U.S. Environmental Protection Agency
Region 5 EPA (WU-16J)
77 Jackson Blvd.
Chicago, IL 60604-3590

Prepared by:

The Cadmus Group, Inc.
57 Water Street
Watertown, MA 02472

Final Report

June 12, 2008

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1.0 Introduction

The Environmental Protection Agency (EPA) was mandated by Congress under the Safe Drinking Water Act (SDWA) to protect current and future underground sources of drinking water (USDWs). SDWA requires EPA to assure that underground injection will not endanger drinking water. EPA's 1987 Report to Congress on Class V Injection Wells determined that Class V injection wells may contaminate, or have the potential to contaminate, USDWs.

Class V injection wells are typically shallow fluid disposal systems that inject fluids (but not hazardous waste) into or above the upper-most USDW. In many situations, Class V wells provide conduits for a variety of wastes to enter the subsurface and ground water. Examples of Class V wells include: industrial waste disposal wells, large-capacity cesspools and septic systems, storm water drainage wells, agriculture drainage wells, and many other types of wells. Many Class V injection wells are "authorized by rule" (40 CFR 144), that is, they do not require a permit if they are in compliance with the UIC program requirements. In some cases, however, EPA requires UIC Program permits be issued to owners of underground injection wells, for the purpose of protecting the quality of USDWs.

This report consists of the evaluation of an application for a UIC Class V permit in Region V. This permit application is for a Treated Water Infiltration System. This report evaluates technical information provided by the permit applicant regarding the hydrogeology and geochemistry of the site, as well as construction and operation of the system. Cadmus is supporting EPA in evaluating whether the proposed system is likely to work as it is intended to, and whether the information provided by the permit applicant is sufficient for this technical evaluation.

This report reviews the adequacy of the data presented in the application (both quantity and quality), and compliance with UIC standards for nonendangerment of underground sources of drinking water, as outlined in 40 CFR 144.12. Specifically, this report 1) discusses existing standards for the design and operation of Treated Water Infiltration Discharges, 2) provides descriptions of existing computer simulation models for this type of system, 3) evaluates the appropriateness of the hydrogeologic model used in the study, 4) analyzes the quality and quantity of the hydrogeologic and water quality data presented, 5) analyzes the hydrogeologic interpretations such as the maps of hydraulic head direction of ground water flow, etc., and 6) reviews the sensitivity analysis performed for the simulation. In addition, this report includes a brief interpretation of the water quality data and touches briefly on the estimates of influent for the WWTP.

2.0 Review of hydrogeologic study and discharge management plan

2.1 Descriptions of background geology

2.1.1 Description of bedrock geology

The hydrogeology study (HS) provides a solid description of the bedrock lithologies and geologic history of the region. The discussion adequately describes the general setting and orientation of the ore body. It does not specifically present the mineralogy of the ore body, which would be useful background information for understanding the generation of acidity in the waters associated with the mine and the role of the WWTP in treating the wastewater. It also does not specify the size of the ore body.

2.1.2 Description of quaternary geology

This section provides a description of the stratigraphy of the quaternary deposits within the environmental baseline study (EBS) area. It includes a general description of each unit, with notes about the grain sizes and major components (e.g., quartz sand, silt, clay, gravel). A more detailed analysis of the mineralogy of the A and D zones is lacking. The description of the quaternary geology does not incorporate information from locations QAL024 – QAL043, where logs from soil borings and monitoring well installations provide more detailed information in the area of the proposed treated water infiltration system (TWIS). It is difficult to evaluate the accuracy of the descriptions because logs are missing from sites QAL001 through QAL023.

2.1 Soil and aquifer testing

2.2.1 Aquifer testing

A single well pumping test was conducted at QAL031D to estimate hydraulic conductivity. In addition, sieve analyses were conducted with the aim of estimating hydraulic conductivity. Data from lab permeameter tests is also presented. Given the heterogeneity and anisotropy of the site, it is likely that only the pumping test data should be taken seriously. Based on the information presented in the application, it does not appear that the conclusions drawn rely on the sieve analyses and lab permeameter data.

2.2.2 Soil infiltration tests

Soil infiltration tests were conducted at 8 locations in the proposed discharge area using a double ring infiltrometer (ASTM D 3385-03). The tests were conducted for approximately 2 hours (until steady-state flow occurred), and measured infiltration rates varied from 61 to 97 cm/hr, which is a reasonable result for the sediment evaluated by these tests.

However, the injection zone at this site is fairly thick (at least 70 feet or 21 meters), and double ring infiltrometer tests are only useful for measuring soil properties for the first few meters below the ground surface. Given the heterogeneity and anisotropy of soil properties at this site, larger scale tests would be more appropriate for providing a realistic infiltration rate under operating conditions for the Treated Water Infiltration System. Both air permeability and water permeability (and their relationship) could be measured via monitoring wells screened in the unsaturated zone. Thus, infiltrometer measurements should be considered inadequate for this application.

2.3 Adequacy of hydrogeologic data, groundwater contours, and cross sections

The background hydrogeologic data for the Yellow Dog Plains were collected from a network of wetland piezometers and groundwater wells. The wetland areas to the south and southeast of the project area are instrumented with 21 wetland piezometers, providing good coverage for the A zone (Figure 9, Appendix A, "A Zone Groundwater Elevation Contours – Spring Snowmelt Runoff, May 2005"). There are limited data provided for the A zone in the project area for the May 2005 sampling (Figure 9), although the few available data points are consistent with a general SW-NE groundwater flow direction. The addition of new monitoring wells (QAL024A, QAL025A, QAL026A, QAL027A, QAL028A, and QAL029A/D) provided better coverage in the project area for August 2005. Although the details of groundwater flow in the western part of the project area could not be clearly defined, reported measurements in the discharge area indicate flow to the NE.

Regional data for the D zone in Figure 10 in Appendix A ("D Zone Groundwater Elevation Contours – Spring Snowmelt Runoff, May 2005") were only sufficient to suggest a general NE flow direction and not sufficient to delineate the hydrogeology of the project area in any detail. The newer wells installed in the summer of 2005 (QAL029A/D, QAL031D, QAL041D) provide three additional data points in the discharge area (Figure 28, Appendix A, "D Zone Groundwater Elevation Contours – Summer Baseflow, August 2005"), but the groundwater in the western part of the project area is still poorly delineated. Furthermore, it is not clear why the seep piezometers to the northeast of the project area were used as data points for Figure 28 and not for Figure 10.

A large area where the D-zone is inferred to be discontinuous is shown to the SE of the project area in Figures 10 and 28. The discontinuous zone is based on only two data points, for which well logs are not provided. However, this discontinuous area is about half a mile to the south/southeast from where the TWIS would be located, and its accuracy is not crucial for interpreting the hydrogeology in the discharge area.

Well logs were not included for the monitoring wells and well nests previously established for the environmental baseline study (QAL001-QAL010). Without this information, it is not possible to fully evaluate the interpretations of subsurface hydrogeology shown in cross sections

B-B', C-C', and D-D' (Appendix A, Figures 21, 22, and 23, respectively). According to the available logs for wells and soil borings in the project area, the transitional deposits (fine sand, silt, and clay) and the lean lacustrine clay are thin and discontinuous in the discharge area, and the A and D zones appear to merge in cross section. Cross sections B-B', C-C', D-D', E-E', and F-F' (Appendix A, Figures 21, 22, 23, 24, and 25, respectively) may in places overestimate the lateral extents of the confining units, and thus underestimate the degree of communication between the A and D zones. In cross section B-B' (Appendix A, Figure 21), for example, the transitional deposit is inferred to span roughly 2,800 feet, from QAL024 eastward to QAL028. In fact, it is not present in the well log for QAL028 and likely pinches out between QAL033 and QAL028. The cross sections shown in Figures 21-25 are best considered general conceptual models, and it should be kept in mind that there may be considerable exchange between the A and D zones given the subsurface heterogeneity. The issue of inaccuracies in the cross sections is likely not a serious deficiency because it is unlikely that greater mounding would occur due to any additional hydraulic connection between the A and D zones. Table 1 in Attachment E of this review summarizes the available data for groundwater monitoring wells and soil borings.

2.4 Water quality

2.4.1 Analytical methods for groundwater samples

The analytical methods used for metals in this study were inductively coupled plasma-atomic emission spectrometry and inductively coupled plasma-mass spectrometry. These methods are appropriate for a variety of environmental samples, including groundwater. Because nearly all metals were below reporting limits, and the reporting limits are often higher than the concentrations in the anticipated effluent, it is difficult to compare the ambient groundwater concentrations with the discharge water. The methods used in this study for major anions are considered appropriate for groundwater, but use of ion chromatography would have permitted lower reporting limits; most sulfate and chloride concentrations were below the laboratory reporting limits.

2.4.2 Completeness of groundwater quality data

Groundwater samples were collected for all seasons from background monitoring well nests to the south, southeast, southwest, and east of the project area (QAL004A/D, QAL005A/D, QAL006A/B, QAL009A/D), and one nest in the NE corner of the project area (QAL008A/D). Well logs were not provided for these monitoring wells. There are no monitoring wells to the NE of the project area, a region that is anticipated to be downgradient of the proposed discharge area. Monitoring in this area during operation of the TWIS would help to evaluate whether mixing of the treated water and the natural groundwater is having an effect on local groundwater quality.

Newer monitoring wells have been installed in the project area, including in the proposed discharge area. Logs for these wells are included in the permit application. However, with the exception of one sample from QAL031D, groundwater chemistry data from these newer wells have not been included in the application. Thus, to date there is little information about the groundwater composition in the immediate project area. Furthermore, no sediment analysis has been done. A mineralogical analysis and/or sediment extractions would be useful for interpretation of the subsurface geochemistry. Without corresponding logs, groundwater chemistry data, and sediment data, speculations about interactions between the groundwater, discharged water, and the sediment must remain extremely general.

Groundwater samples were analyzed for 21 trace metals, as well as for major cations and major anions. The analyses include metals of concern in an area with massive sulfide ores (e.g., Cu, Ni, Zn, Pb). Small amounts of mercury were routinely detected, but the analyses were problematic, with frequent mention of contaminated blanks and difficulties with precision. Samples were not analyzed for organic carbon, nor were they analyzed for sulfide. No information is provided regarding how the samples were filtered; some of the more insoluble metals (e.g. Al, Fe^{3+}) are likely present as colloids. Because filtration was not described and speciation was not done, it is difficult to interpret the water chemistry analyses.

Complete groundwater quality data are needed in the project area and under the proposed discharge area. Dissolved oxygen and ferrous iron were generally not measured for QAL008A/D, which is located at a corner of the TWIS area, or QAL009A/D, which is located just east of the project area. Dissolved oxygen was not measured for QAL031D, which is located in the proposed discharge area. This information is needed for considering the impact of the discharged water on the chemistry of the native groundwater. In the absence of complete groundwater analyses in the discharge area and of sediment analyses, interpretations of the subsurface geochemistry must remain general and speculative.

In summary, the groundwater analyses provide basic information on major constituents and on a suite of trace metals that may be problematic in an area with massive sulfide deposits. But relatively few groundwater samples were taken from the proposed discharge area, dissolved oxygen and ferrous iron were not consistently measured, and data are lacking downgradient from the discharge area.

2.4.3 Interpretation of groundwater quality data and potential for impact of effluent on groundwater quality

The groundwater in the D-zone is generally anoxic to the south, southwest, and southeast of the project area and contains dissolved iron, dissolved manganese, and low levels of arsenic. Other heavy metals may be present at levels below the reporting limits. Because of health issues, arsenic is of particular concern. It is likely that microbial activity in the aquifer has resulted in the reductive dissolution of iron and manganese oxides. According to staff at the Michigan

Geological Survey, the sandy glacial sediments in the area of the Yellow Dog Plains are nearly entirely quartz sand with minor amounts (<1%) of feldspars and other minerals. Soil boring logs indicate that the sediments are generally light brown or reddish brown, indicating the presence of iron oxide coatings on the sand grains. Arsenic is known to co-precipitate with iron oxides, and the reductive dissolution of iron and manganese oxides has likely released arsenic into the groundwater.

Groundwater in the A zone, on the other hand, has measurable dissolved oxygen and <2 μg/L of arsenic. Unless conditions in the discharge area become consistently anoxic, it is unlikely that significant arsenic will be released from the sediments due to redox changes. The projected effluent composition does not contain an estimate of dissolved oxygen, but the discharge water should become reasonably well oxygenated during storage, treatment, and transport to the infiltration gallery. The estimated effluent composition also does not contain an estimate of organic carbon. Dissolved organic carbon is perhaps not likely to be high in the effluent. This could be verified by testing.

Although this region contains a massive sulfide deposit, the highly weathered nature of the sediments suggests that the majority of any minor sulfide minerals will have already been oxidized. Thus, oxidation of sulfides in the A zone by discharge water is not likely to be an issue. Mineralogic analysis of the sediment would provide confirmation of this.

Because the A and D zones are in communication in the discharge area, it is expected that the groundwater will not generally be completely anoxic. The nearest upgradient well nest with dissolved oxygen measurements is QAL004A/D, where dissolved oxygen concentrations in the A zone range from 5 to 7 mg/L. Introduction of oxygenated water from the TWIS should not cause an extreme change in redox conditions in the aquifer. This could be verified by groundwater sampling in the discharge area and downgradient.

The amounts of ammonia projected to be in the groundwater are below the Michigan Part 201 Residential Drinking Water Criteria (R299.5744) and should not present a direct water quality threat if they remain similar to the anticipated concentrations. The behavior of nitrogen in groundwater is complex. At the pH of the groundwater, the ammonia will be present primarily as ammonium, some of which may sorb to aquifer materials, retarding its movement. Some may undergo nitrification (oxidation to nitrate), with generation of acidity. The degree of nitrification will be affected by temperature, dissolved oxygen, and salinity. Although it is difficult to predict without more complete characterization of the aquifer, the low groundwater temperatures (5 – 8 ^{o}C) suggest that nitrification will be slow. Furthermore, based on the slightly basic pH and high alkalinity of the ambient groundwater, it can be inferred that the mineralogy of the aquifer may include small proportions of carbonate minerals, which would buffer minor changes in pH.

The ionic strengths of both the ambient groundwater at QAL008A and the projected effluent concentration are similar (around 0.0010-0.0014). Among the major ions, the anticipated sodium and chloride concentrations in the effluent are much higher than in the ambient groundwater. Calcium and magnesium concentrations, on the other hand, are lower in the effluent than in the groundwater. Elevated sodium chloride levels (such as from de-icing contamination from roadways or in estuarine settings) are known to mobilize metals in soils and sediments. However, the sodium and chloride contents in such settings are much higher than what is predicted in the treated water described in this permit application, and such studies are generally focused on contaminated soils and sediments. The waters to be dealt with in this project are relatively dilute and shifts in major ion chemistry might not have significant effects. Possible mobilization due to sodium and chloride may be offset by the lower calcium and magnesium concentrations.

It is also not known if the sediments contain significant metals available for mobilization. Based on groundwater data from the various background wells, the aquifer sediments may pose potential problems with arsenic and possibly mercury. Problems with other metals are not expected, although no sediment analyses are available. Groundwater monitoring during TWIS operation would indicate if mixing of treated water with the native groundwater leads to any unexpected constituents in the groundwater. On the other hand, a simple laboratory test could be conducted prior to TWIS operation, where aquifer sediments would be leached with water with the anticipated treated water composition (using native groundwater as a control). This would indicate if these differences in major ion chemistry will have an effect on the interaction of groundwater with the sediments.

The likelihood that the infiltration system will pose a threat to a USDW depends upon the composition of the treated wastewater. A good estimate of the composition of the treated wastewater depends in turn upon a solid evaluation of the expected mine drainage. The geochemical report in Attachment 2 of the application (Water Chemistry of Mine Drainage Water and TDRSA Water, submitted by Geochimica, Inc.) describes the estimated chemistries of the mine leakage and the water from the temporary development rock storage area (TDRSA). The material included in this application is a technical memorandum rather than the full report. Therefore, limited information is presented. It is beyond the scope of this review to evaluate the leaching tests and procedures used to calculate the mine drainage water chemistry. However, if a sensitivity analysis of the calculations had been performed it would have been possible to develop a more robust evaluation of the potential WWTP influent and effluent compositions and, consequently, of the potential impacts to groundwater. The study might also have benefited from consideration of any seasonal effects on the runoff from the TDRSA. The permit application did not include information on other forms of mine-related runoff (e.g., truck wash). While it is possible that truck wash water would have significant amounts of fine particulates including ore minerals, it is likely that such material would be removed in the wastewater treatment plant, if such runoff can be effectively captured and directed into the plant, and if the plant functions effectively and is able to handle the additional volume of wastewater.

Strictly on a design basis, the WWTP should be able to achieve the water quality parameters provided in Table 1-1 (Wastewater Flows and Pollutant Concentrations) in Appendix C. The combination of precipitation and reverse osmosis (RO) should be able to achieve low levels of metals. The calculations appear to have been performed using the higher ends of the listed removal rates in some cases (especially chloride), so if the influent water quality were significantly worse than what was listed, the effluent might contain higher concentrations.

There may be operational issues to contend with. For example, RO membranes are known for scaling and clogging, especially due to calcium, sulfate, silica, and iron. Precipitation should remove most of these ions, but as the applicants note, the concentrations will depend on the solubility of the various ions at a given pH. The plans specify a tentative pH range, but do not specify how removal will be optimized. Regardless, the RO membranes may need to be cleaned or replaced fairly often, especially given the high sulfate concentrations expected in the filtered clarifier effluent. The proposed dual train arrangement will be helpful in this regard.

2.5 Discharge management plan

2.5.1 Capacity of the soil to handle proposed hydraulic loading rate

The calculated loading rates and the area of the TWIS were calculated using infiltration rates from QAL037, which were among the lower values (approximately 50-70 cm/hr) and, therefore, represent a conservative estimate. Rates at other test locations ranged up to 100 cm/hr. The anticipated loading of 0.5 ft/day is well within the capability of the soil, which is at least 47 ft/day. As noted above, however, the subsurface geology at the site is heterogeneous and infiltration rates measured at the surface are not necessarily representative of the sediments at depth.

2.5.2 Design standards for injection wells containing treated mine waste

Cadmus has reviewed design standards to determine applicable standards for the construction of a Class V UIC injection well injecting treated wastewater from a mining operation. The proposed well is located in the Upper Peninsula of Michigan; therefore, cold weather concerns were also examined.

A Class V injection well is defined as any device used to inject nonhazardous waste into a shallow aquifer. This covers a wide variety of wells in respect to both construction and purpose. An EPA study on Class V wells identified 25 types of injection wells (EPA, 1999), with some types having several subcategories. The well type covered in this document does not fit into any of those categories. One category, mine backfill wells, is similar, but it differs in important respects from what is being proposed. Mine backfill wells return the water to the mine, whereas the proposed well disposes of the water to a shallow aquifer after treatment. Backfill wells also typically use standard well construction techniques with a vertical drilled hole surrounded by casing. The proposed well consists of a horizontal infiltration gallery.

Construction is more important than type of waste injected in determining design standards. A review of the literature indicates that the proposed construction most closely resembles the design of on-site wastewater infiltration wells. These wells typically use galleries of horizontal perforated pipe to introduce wastewater into shallow gravel-filled buried trenches. The wastewater then percolates through the soil into underlying aquifers. Although the type of waste injected and the need for treatment in the soil is different, the basic design principles should be the same. Other well types that use horizontal piping laid in trenches to inject water into shallow aquifers include some aquifer storage wells and storm water drainage wells. The design standards for these classes of wells can be discussed under four headings: site selection, piping and trench design, construction, and operation and maintenance.

2.5.2.1 Site selection

In determining a site for an infiltration trench, the most important parameter is the ability of the soils to accept the amount of water injected without the water running offsite. Generally, the soil should be free of impermeable layers such as clay. Sandy soils or sandy loams are generally the most appropriate. Often, a minimum soil infiltration rate is set. For example, the State of Kansas recommends values above 0.6 inches per hour. The Army Corps of Engineers has noted that many methods for measuring soil permeability give much higher values than are actually experienced under field conditions. For design purposes, they recommend using permeability values much lower than measured values. The recommendations are to use a value of 4 to 10 percent of clear water permeability values, 10 to 15 percent of measured basin infiltration rates, and 2 to 4 percent of values obtained by cylinder infiltrometer measurements (USACE 1982). The infiltration rates obtained by ring infiltrometer were 61 – 97 cm/hr. Using the lower value, this represents an infiltration rate of 48 ft/day. Two percent of 48 ft/day is 0.95 ft/day, which is greater than the proposed application rate of 0.5 ft/day. The applicant has, therefore, proposed a loading rate that is within the safety margin recommended by the Army Corps of Engineers. Thus, at least near the surface, the soil should be able to handle the loading rate of the released water.

To prevent water from running offsite, it is recommended that injection galleries be constructed on flat land. Slopes greater than 12 percent are considered poor locations for infiltration galleries (USACE 1982). Sites should generally be laid out to be parallel to topographic contours. Topographic contours on the maps provided by the applicant are difficult to read precisely, but it is clear that there are few contour lines in the area of the TWIS, and the topography is relatively flat. Generally, a groundwater mounding analysis is performed to predict how the injection will affect groundwater flow and to ensure that the groundwater will not rise above the bottom of the injection zone. To protect against groundwater rising above the bottom of the injection zone, a minimum separation distance is often recommended between the bottom of the injection zone and the high water mark of the water table. Recommended distances vary between 2 to 6 feet. At the proposed site, the unsaturated zone is tens of feet deep; groundwater should not rise above the bottom of the injection zone.

To prevent contamination of drinking water, setback distances are usually recommended from drinking water wells and surface water. Typical distances are 100 feet from drinking water wells. Drinking water wells are not noted in the project area on any of the maps associated with this application.

2.5.2.2 Piping and trench design

The infiltration galleries consist of cells of perforated pipe laid in shallow trenches. The area immediately surrounding the pipes is usually surrounded by gravel to aid percolation into the soil. A void fraction of 30 to 40 percent is desirable. Gravel is usually ¾ to 2½ inches in diameter and should be washed and graded. It should be durable and resistant to slaking and dissolution to prevent clogging of the pore spaces. A hardness of greater than 3 on the Mohs scale is recommended (USEPA 2002). (The Mohs hardness scale indicates the relative hardness of minerals on a scale of 1 to 10, with 10 being represented by diamond, the hardest mineral. A mineral with a hardness of 3 is easily scratched and is represented by the mineral calcite. The most common rock-forming minerals, such as quartz and feldspars, have a hardness of at least 6.) Very often a sand layer is included under the gravel to further aid percolation into the soil. A geotextile fabric is laid over the gravel to prevent soil from clogging the pore spaces. The fabric should be selected on the basis of strength and should be away from roots and other items that could cause punctures. Schematics provided by the applicant show a cross section of a trench with the pipe surrounded by gravel underlain by sand and covered by a geotextile fabric if required.

The piping should be perforated along the bottom. Perforations are typically slots or circular holes. For wastewater designs, 4-inch plastic pipe is typically used, although other types are used as well. In the proposed TWIS, the piping would be 1½″ -diameter schedule 40 PVC. If water is injected under pressure, stronger pipe may be required. The pipe, along with all other appurtenances such as pumps or siphons, should be resistant to corrosion from the injected fluid. With the high concentration of chloride in the treated mine water, this will be particularly important. Piping should conform to applicable standards (e.g., ASTMD2729-93 for PVC pipe). Injection velocities should be designed to be low enough not to cause erosion in the surrounding soil or to cause corrosion of the piping and appurtenances from abrasion.

Infiltration galleries are generally designed as cells of pipes spaced 3 to 6 feet apart. It is recommended that each cell be designed to accommodate 100 to 150 percent of the expected flow. This allows for variations in flow and provides for spare capacity in case of cell failure. It also allows for rotation of cells. In the proposed TWIS, the pipes will be spaced 10 feet apart, and the orifices will be spaced 10 feet apart.

2.5.2.3 Construction

The important considerations in construction are preventing compaction of the soil, which would reduce permeability, and avoiding the introduction of fine matter into the trenched area, which can reduce permeability by filling void spaces. To achieve these goals, it is recommended that the site be staked off and heavy machinery be kept off during construction. Excavation should generally be done by light equipment with treads or oversized tires. Gravel should be placed in the trench using a backhoe instead of being dumped directly from the truck. Soil should be below the plastic limit at the time of construction (USEPA, 2002). Construction should be completed as quickly as possible and should be covered at the end of the day to avoid entry of windblown silt and dust.

2.5.2.4 Operation and maintenance

Operation and maintenance procedures are important to the functioning of any injection facility. It is recommended that a set of standard operating procedures be published for every injection facility. Recommended items to include in regular operation and maintenance include daily meter reading, monthly inspections, and annual rotation of injection cells. In the proposed TWIS, one of each of the five cells will rest each month. Inspections should include checking pumps and siphons and making sure the injection area is free of roots and sediment. The proposed TWIS would be equipped with computerized monitoring of flow to the TWIS, flow in each cell, water level in each dosing chamber, and which cells are in operation.

2.5.2.5 Cold weather factors

There are several factors that may need to be adjusted for facilities in cold climates. The pipes will need to be far enough underground to prevent freezing of the injectate. Generally, 1 to 2 feet of soil over the pipes will be sufficient (USEPA 2002). Also, permeability will be lower in cold weather, so the minimum design permeability should be increased. Distribution blocks for the cells should be built on frost-proof footings to prevent damage. If the piping is not surrounded by gravel, the site should be placed 20 feet away from roads and other paved areas to avoid frost heave.

3.0 Review of modeling

3.1 Background

The hydrogeologic simulations include the application of a two-dimensional analytical model using MOUNDHT and two three-dimensional numerical models using MODFLOW. The analytical calculations of groundwater mounding below the infiltration system are presented in Appendix E, entitled “Groundwater Modeling of the Treated Water Infiltration System.” The

Appendix prepared by Foth & Van Dyke (F&VD) is in the form of a memorandum, dated January 11, 2006, and was originally submitted to the Michigan Department of Environmental Quality by the Kennecott Eagle Minerals Company. The first three-dimensional numerical model is presented in "Groundwater Flow Model of the Treated Water Infiltration System," prepared by Golder Associates (Golder) in the report dated April 21, 2006. The second three-dimensional numerical model is presented in "Supplemental Hydrogeologic Study for Groundwater Discharge, Kennecott Mineral Company Eagle Project," prepared by North Jackson, dated January 2006. It is unclear why Kennecott Minerals contracted for two numerical models during the same time period. The model areas and constructions are similar and both models were used to predict the effects of mounding.

3.2 Review components

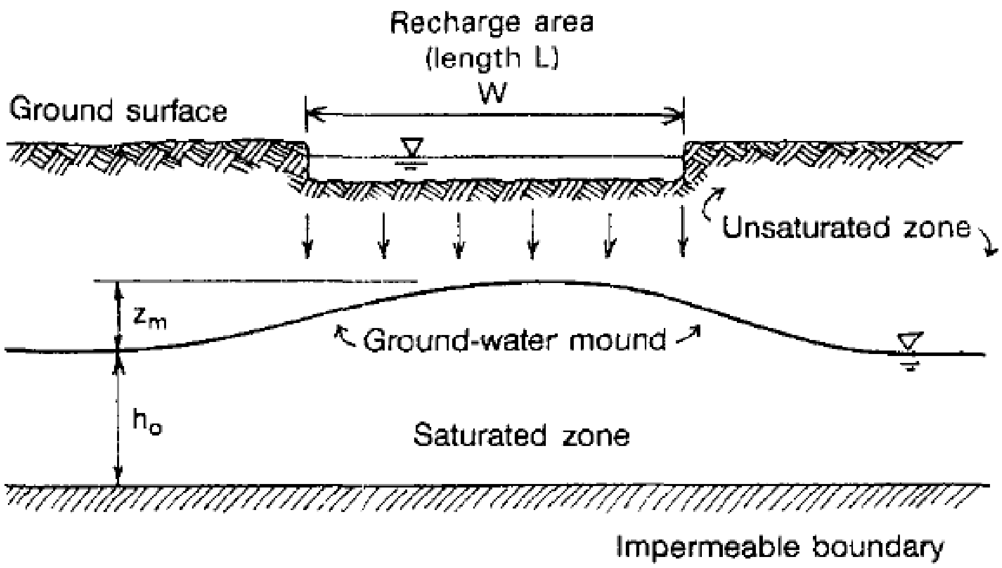
This review is comprised of six components:

1. Existing computer simulation
2. Appropriateness of hydrogeologic model
3. Quality and quantity of data used in modeling
4. Sensitivity analysis performed
5. Calculational check
6. Overall quality of modeling study

3.2.1 Existing computer simulation

The computer simulations include the application of analytical and numeric models. Each is independent, however, the analytical model was used to help guide the development of the numerical model.

The groundwater modeling was analyzed using an analytical solution originally derived by Hantush, 1967. The model assumes the porous media is isotropic and that the aquifer is unconfined and of infinite extent. The model predicts the water table height (groundwater mound) under steady-state flow conditions subject to uniform infiltration over a rectangular area. A program to calculate the mound heights is presented by Finnemore (1995) in the computer notes of Ground Water Journal. The author developed a FORTRAN computer code named MOUNDHT to solve the equations.



From Finnemore, 1995.

The MOUNDHT computer program was not obtained and instead a commercially available computer program was used in the review to check the calculations. A well test program, AQTESOLV, has been expanded to solve the Hantush equations (Attachment A). The computer program solves the same equations as used by F&VD and extends the applicability by solving for both rectangular and circular infiltration areas. The program additionally applies the theory of superposition and allows for incorporation of linear boundary conditions of no-flow and constant head. Using an alternative calculation method provides confidence that the solution procedures are the same and that there is less chance of error in understanding the model inputs and output (Section 5).

The analytical model is limited to assessment of the uppermost glacial outwash and beach deposits (Zone A). The predicted magnitude of the height and extent of the mound were used to guide the construction of the more complex numerical model.

The numerical model application by Golder uses the USGS finite-difference model MODFLOW (McDonald and Harbaugh, 1988). This computer code is freely available. There are several commercially-available user interface programs. Golder used the GMS software. The model is a steady-state representation of water table conditions of all Quaternary deposits within 2 miles of the infiltration site. The level of model complexity can be described as “simple,” although generally adequate for the intended purpose.

3.2.2 Appropriateness of hydrogeological model

The analytical model was found to be generally appropriate for the hydrogeologic conditions at the site and the intended purpose of the model. The model is applied to the glacial outwash and beach deposits (Zone A) which are under water table conditions. The model assumes that there is no leakage through zones B&C although this is actually discontinuous with the area of interest. This assumption in the model is reasonable as limiting the analysis to Zone A results in the maximum predicted height of mounding. There is likely to exist horizontal-to-vertical anisotropy at the site that is not included in the analytical model. It is assumed that the sole purpose of the analytical model is to provide guidance for later development of the more complex numerical model although this is not explicitly stated. The height and extent of the mound are used to determine the aerial extent of the numerical model.

The Golder numerical three-dimensional MODFLOW application includes Zones A through D and represents the layers in a step-wise, stair-cased grid arrangement. The model is not based on readily available elevation data (DEM), nor does the model include the numerous surface water discharge features, also readily available (National Hydrology Data, nhd.usgs.gov) in GIS format. The model includes hydraulic parameter variation by zone. The boundary conditions are simplistic constant head and no-flow edges. These assumptions are judged as generally appropriate, however, it should be noted that the simplifications of grid elevation control, lack of surface water features and boundary conditions detract from the specificity of the model.

Figure 1, below, was created using readily available GIS files (www.mcgi.state.mi.us/mgdl) and Table 1 from North Jackson. The model grid is approximately the Golder model. Note that the watershed boundaries are significantly different from the groundwater divide presented in the two modeling reports.

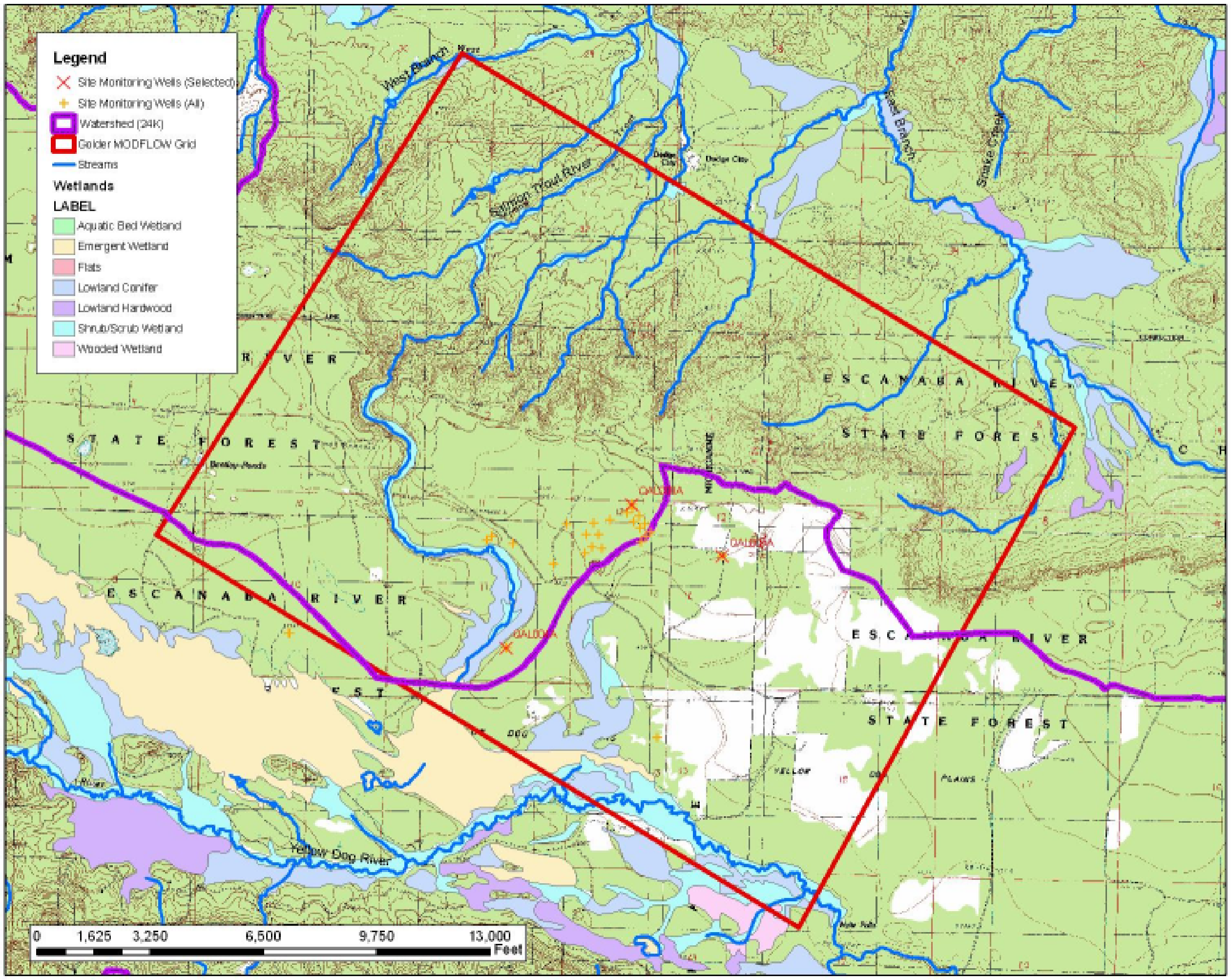


Figure 1. Site location with watershed boundaries, wetlands and selected monitoring wells.

It is not clear whether the numerical model included the Peridotite dike. Because the predicted contour lines do not show breaks, it is likely that this intrusion was not incorporated into the model. The model underpredicts the mounding in close proximity to the dike.

Net recharge from precipitation was not included in the numerical model. The Michigan Geographic Library provides estimates of net recharge to the glacial sediment from precipitation in GIS format. Using baseflow in streams, Neff, et al., 2005 estimate that there is 13 inches per year in the Ives Hill quadrangle near the site. (www.mcgi.state.mi.us/mgdl/?rel=ext&action=sext). Recharge is an important component for this model and is about twice the regional horizontal groundwater flow (Attachment B). Relative to basin infiltration, recharge is approximately 200 times less.

The North Jackson numerical three-dimensional MODFLOW application includes Zones A through D. Presumably the model includes elevation changes, though details are not provided. The North Jackson model uses at least five model layers whereas the Golder model uses only three. The North Jackson model extends to watershed boundaries or rivers and what appears to be flowlines. The Golder model extent is less and the boundaries are more simple and arbitrary. The North Jackson model appears to include surface effects of at least a dozen reaches along Salmon Trout and Yellow Dog Rivers. The Golder model does not include any surface water discharges or wetland areas.

3.2.3 Quality and quantity of data used in modeling

The critical model parameters include:

- Horizontal hydraulic conductivity,
- Initial aquifer saturated thickness,
- Specific yield,
- Time or duration of infiltration,
- Dimension of infiltration area, and
- Infiltration rate.

The analytical model parameters selected are generally conservative. The selected value of hydraulic conductivity (25 ft/day) is consistent with recent aquifer testing and less than the Zone A value of 61 ft/day reported by F&VD, 2005 and the average value of 50 ft/day as reported by North Jackson, 2006. A lower value of hydraulic conductivity results in a greater predicted mound height. Two values of specific yield are used. The representative value of 0.15 is appropriate for sand, and a more conservative value of 0.05 was used resulting in greater predicted mound height.

The numerical model parameters selected are similar, although details of the North Jackson model are not provided.

3.2.4 Sensitivity analysis performed

The analytical and Golder numerical models were run through a limited number of sensitivity analyses. The purpose of a sensitivity analysis is to help address and understand which components of the model inputs have the greater and which have the lesser impact or influence on the predicted results. Examination of the sensitivity of calibration residuals and model conclusions to model inputs is a method for assessing the adequacy of the model with respect to its intended function (ASTM 5611). The analytical model included variations of hydraulic conductivity, initial saturated thickness, infiltration rate and specific yield. Expectedly the calculations are most sensitive to the infiltration rate. Overall the level of sensitivity analysis is judged as being marginally adequate for the modeling purposes.

The Golder numerical model sensitivity analysis was limited to variations in the hydraulic conductivity. Only one additional case was run in which the conductivity was nearly doubled. The report only briefly describes a sensitivity case using a lowered value of effective porosity. The level of sensitivity analysis is judged as marginal at best.

The boundary conditions used in the Golder are highly constrained rendering the model rather insensitive to changes in the hydraulic conductivity. The model would be more responsive and robust if the grid were extended slightly further to the watershed and presumable groundwater basin edges. This would, of course, require that some surface water head-dependent boundary conditions be incorporated to provide uniqueness to the solution. This strategy would allow the predicted heads to more freely float.

The North Jackson numerical model is not well documented and no sensitivity analyses were performed.

3.2.5 Calculational check

To ensure that the analytical model calculations are correct a comparison between two models is presented in the table below. The calculated maximum groundwater mound rise in feet at the center of the mound after 365 days of infiltration compares favorably between the two models (See Attachments C and D for details of the two scenarios).

Scenario	MOUNDHT	AQTESOLV
1	33.3	33.28
2	29.6	29.64

Additionally the shape of the groundwater mounds is compared. The original models provide for contours of the mound for Scenario 2. The rectangular area is 150 x 1027 feet. There arrears to be a slight error in F&VD Figure 2. The ¼ patch rectangle should be 75 x 514 feet, but appears to be approximately 75 x 750 feet.

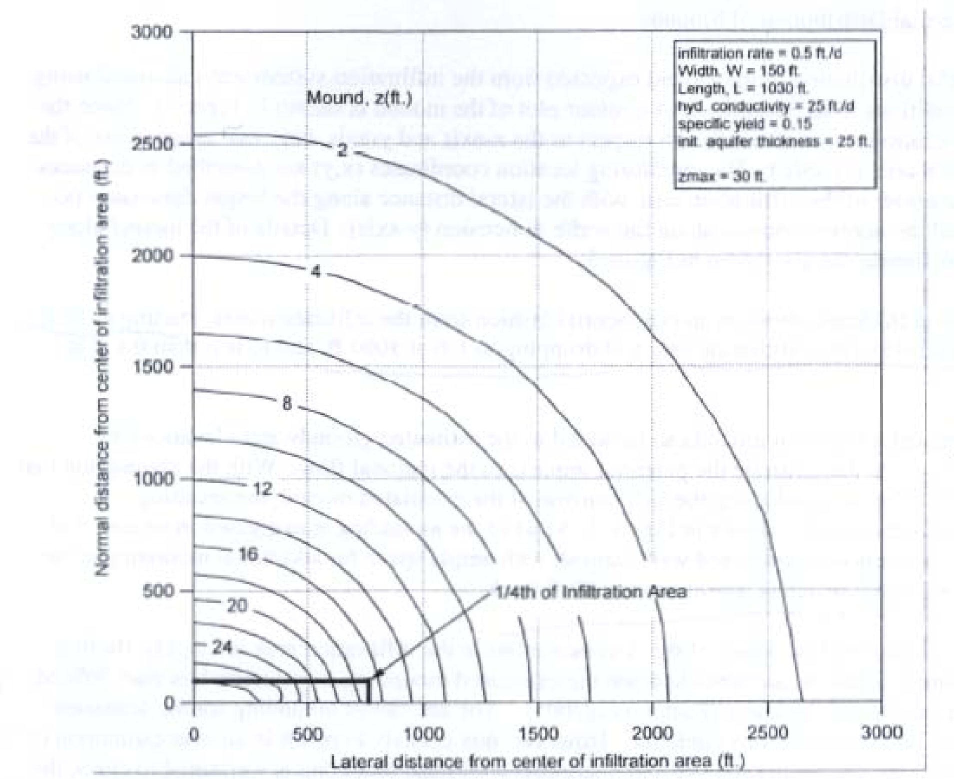
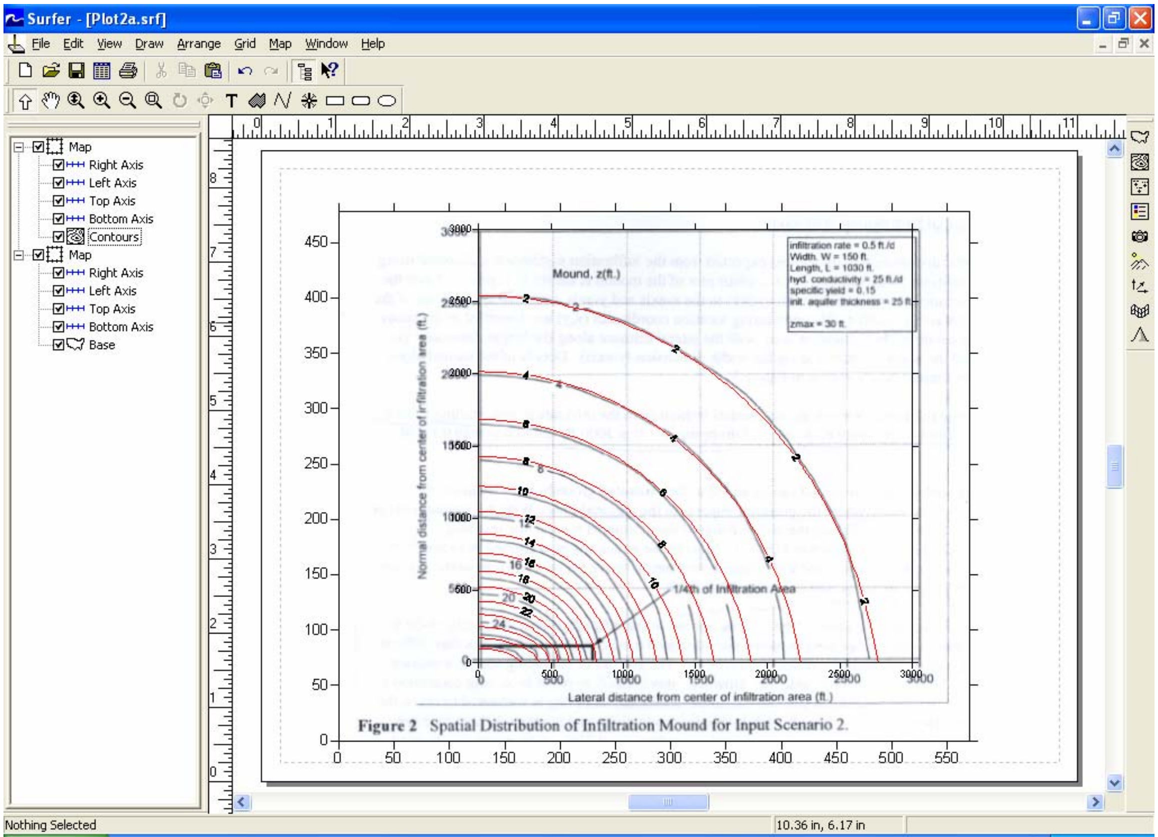


Figure 2 Spatial Distribution of Infiltration Mound for Input Scenario 2.

From Foth & Van Dyke, 2006.

Using AQTESOLV (shown in red), similar results are obtained as shown below. Except for differences resulting from the contouring approaches used, the results are very similar. This indicates that the two sets of calculation results are consistent and probably correct.



Comparison of F&VD analytical solution and AQTESOLV predicted mounding.

Using AQTESOLV, the analytical model can be further extended to address the effects of boundary conditions. The F&VD analytical solution assumes infinite boundary conditions, however, the Peridotite dike intrusion is located approximately 1,200 feet upgradient of the recharge site and is a potential localized flow barrier.

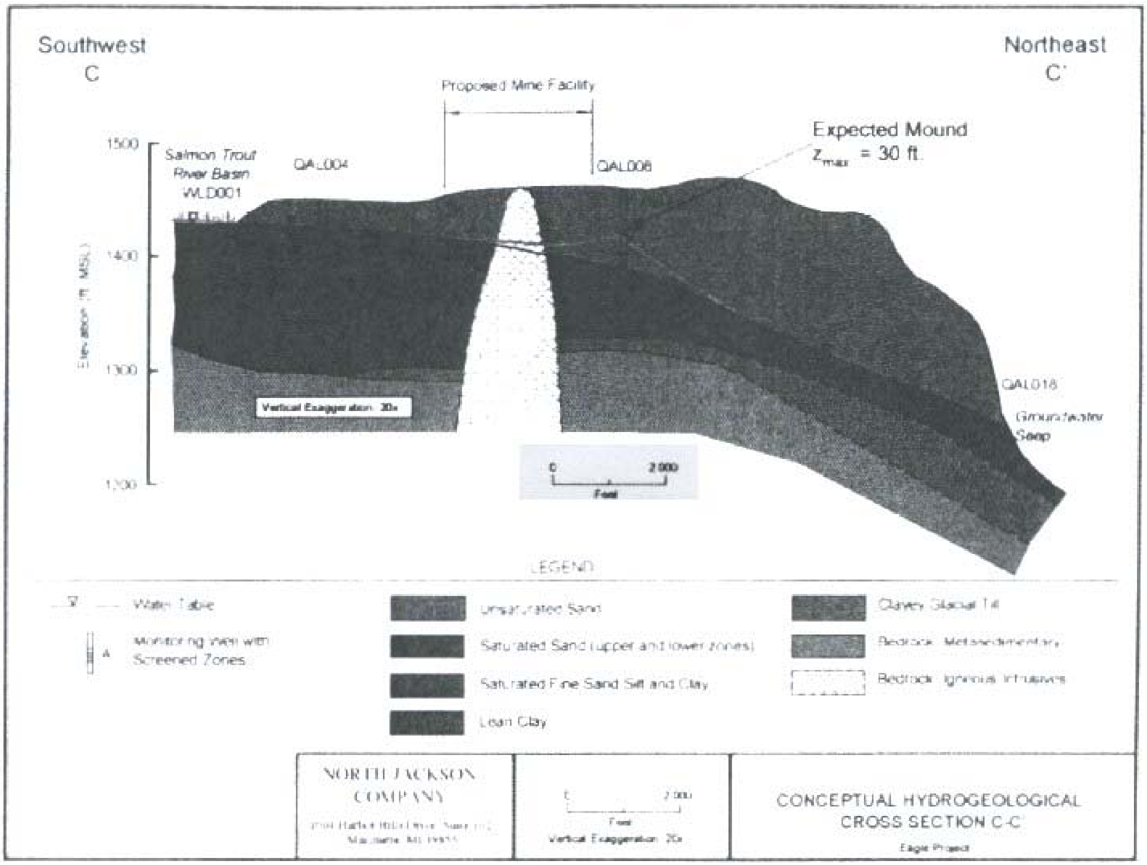


Figure 2. Conceptual Hydrogeological Cross Section C-C'. From Foth and Van Dyke, 2006

The dike appears to be located at a point where the predicted mounding is about 9-10 feet as shown in Figure 3 by F&VD.

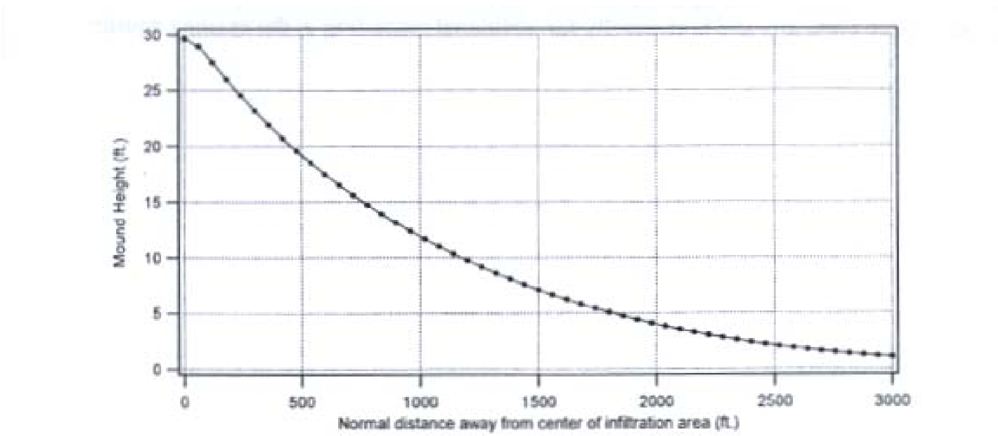
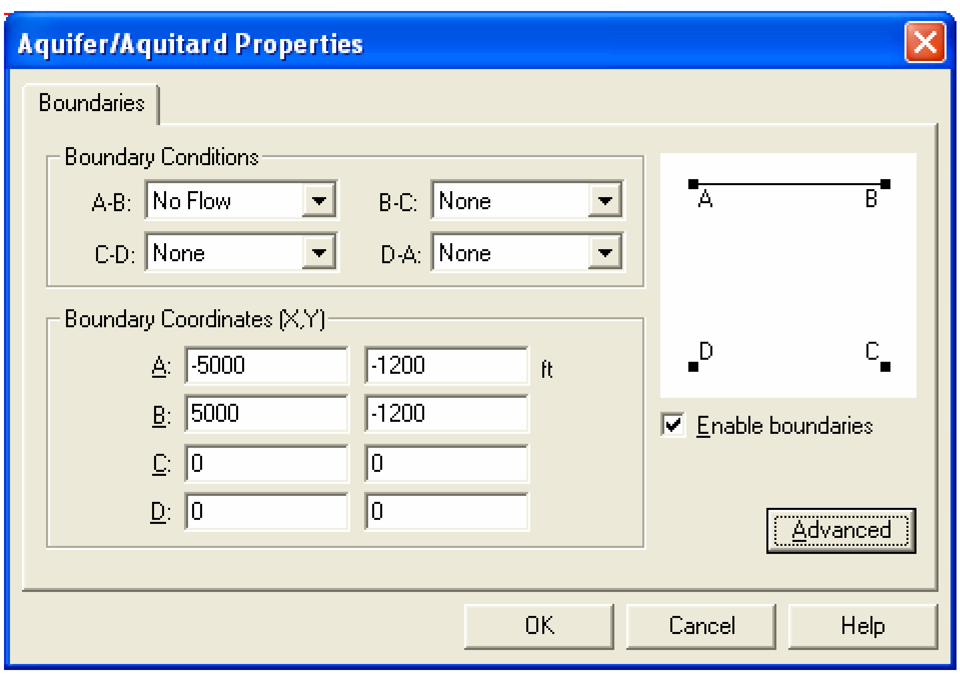


Figure 3 Detail of Infiltration Mound with Normal Distance (y-dimension) for Input Scenario 2.

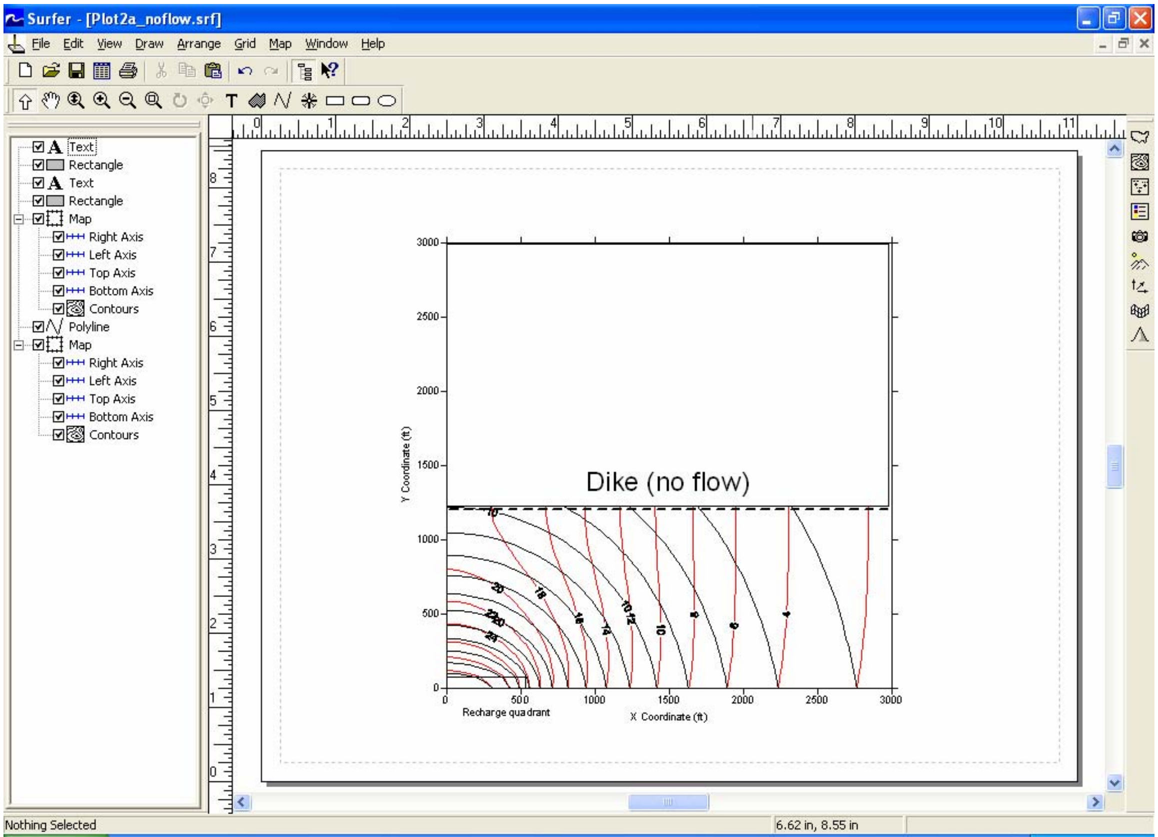
From Foth and Van Dyke, 2006.

The dike is nominally 500 feet in diameter and most likely behaves more like a partial no-flow barrier. To include this effect AQTESOLV offers boundary condition options. To assess the importance of the dike a test simulation was run in which the dike was assumed to be of infinite extent. A no-flow boundary is established at 1,200 feet as follows:



Placement of no-flow boundary. (Menu from AQTESOLV).

When the dike is added to the model, the mound near the dike increases from 10 to 19 feet although the maximum mound beneath the center of the infiltration zone is nearly unchanged.



Comparison of F&VD and AQTESOLV with no-flow boundary

This indicates that incorporation of the dike has no significant effect on the height of the mound beneath the infiltration site, but may locally increase mounding in the vicinity of the actual dike.

There was no calculational check made on the numerical MODFLOW models. The data set for the Golder MODFLOW was not available in the report, nor was there sufficient data provided in the report to easily reproduce the numerical model. Furthermore, the grid origin and axis rotation are not provided thereby making GIS checking difficult. This is very significant, because without running calculations checks it is not possible to ensure that convergence of the iterative solution was achieved, that adequate closure was accomplished, that acceptable mass balance was achieved and that graphics are representative of the model calculations. It is assumed that the water table option in MODFLOW was used, at least for Layer 1 (Zone A). However, this may not be true as the predicted water table surface as shown in Figure 16 shows several "flooded" cells. In other words, it is not known whether the equations for confined or unconfined conditions were applied which would have some effect on the predicted water table configuration.

Based on the graphics presented, it would appear that rewetting of dewatered cells was not encountered. MODFLOW can often be troublesome in dealing with cells that are predicted to fully dewater during the solution procedure. Had more than one model layer been used to represent Zone A, these sorts of numerical challenges would have likely been encountered.

The description and basic information of the North Jackson model were not provided, therefore no calculation checks were performed.

There are no mass balances reported for either of the numerical models. All MODFLOW models report should include mass balance disclosure and discussion of the solution procedure used. A generally accepted criteria is that a mass balance of less than 1 percent error be achieved in order to accept that the calculations are correct.

3.3.6 Overall quality of modeling study

The overall quality of the model results in the reports is judged as fair to poor. The modeling strategy is appropriate for site conditions and intended modeling purpose.

Because there was no attempt to calibrate the numerical model, this detracts significantly from the quality and credibility of the modeling. Anderson and Woessner (1992) define calibration as a demonstration that a model is capable of producing field-measured (observed) water elevations and/or discharges within a pre-established range of error. Calibration of a numerical groundwater flow model is achieved by adjusting the model hydraulic properties or conditions (calibration parameters) to obtain a match between observed measurements (calibration targets) and model-predicted water elevations within a pre-established acceptable error (the calibration goal). The lack of model calibration erodes confidence that the predicted water elevations and discharges are representative of actual field conditions and believable.

The quality of the model documentation does not provide adequate detail to fully assess the numerical model predictions. In general the modeling standards applied are judged to be fair quality, but do not provide details for a thorough assessment. While the numerical model is somewhat simplistic in the level of detail, the model appears to provide reasonable predictions of the height and extent of the groundwater mound beneath the infiltration site.

None of the reports reference nor fully follow the numerous ASTM groundwater modeling standards.

The Golder numerical model has some significant limitations as stated in the report:

- Uniform properties and uniform hydrostratigraphy
- Lacks numerous surface water discharge features
- Approximate boundary conditions of no-flow and constant head that are sufficiently far from the infiltration areas.

The model understates the limitations of:

- Discontinuities in the confining Zone B & C
- Stepwise elevation grid control
- Does not include Peridotite intrusive dike
- Possibility of buildup of water within the water infiltration system

The model conclusion that the water table will rise by 2 feet at a distance of 3,500 to 7,500 feet is reasonably sound. It is unlikely that enhancements to the numerical model would change this conclusion significantly. However, because the model lacks surface water features and recharge from precipitation, there is uncertainty as to distribution and extent of the mound. Without incorporating the seeps to the north, the model predictions are likely an overestimate of the magnitude of the mounding.

The model does not provide prediction of changes to discharge to Salmon Trout River, either in terms of water quantity or quality (chemical and temperature). The model cannot be used to determine the impact on wetlands either. These omissions may be a significant deficiency with regard to the ecological impacts and detract from the report quality and credibility. Because this is outside the scope of the UIC review, this was not investigated further.

The model does provide reasonable evidence that the glacial deposits do provide adequate hydrogeologic capacity to assimilate the additional infiltration without inundating the site. In other words, the calculations show that a mound will be created raising the water table, and will probably maintain a significant unsaturated zone beneath the site.

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Attachment A

Groundwater Mounding Theory – (Copied from AQTESOLV computer program)

Rectangular Recharge Area - the transient rise of the water table beneath a rectangular recharge area using a solution by Hantush (1967).

$$h^2 - h_0^2 = Z(x,y,t) = \frac{\upsilon w}{K}\int_0^t \left[erf\left(\frac{l/2+x}{\sqrt{4\upsilon t}}\right) + erf\left(\frac{l/2-x}{\sqrt{4\upsilon t}}\right)\right]\left[erf\left(\frac{a/2+y}{\sqrt{4\upsilon t}}\right) + erf\left(\frac{a/2-y}{\sqrt{4\upsilon t}}\right)\right]$$

$$\upsilon = K\bar{b} / S_y$$

$$\bar{b} = 0.5[h_i(0) + h(t_1)]$$

where

- a is dimension of the recharge area in y direction [L]
- h is the head beneath the mound [L]
- h_0 is the static head prior to recharge (i.e., initial saturated thickness of aquifer) [L]
- K is the hydraulic conductivity of the aquifer [L/T]
- l is dimension of the recharge area in x direction [L]
- S_y is the specific yield of the aquifer [dimensionless]
- t is time [T]
- t_1 is time used in successive approximation [T]
- w is the recharge rate [L/T]
- x is coordinate of the observation point [L]
- y is coordinate of the observation point [L]

The decay of the water table is found using the principle of superposition (Hantush 1967):

$$h^2 - h_0^2 = Z(x,y,t) - Z(x,y,t-t_0)$$

where

- t_0 is the time when recharge stops [T]

Attachment B

The infiltration rate from the Treated Water Infiltration System is significantly greater than the net infiltration from precipitation. For the model area, the regional horizontal groundwater flow is similar in magnitude to net infiltration from precipitation. The calculations below are based on model input parameters presented in the application.

Infiltration from Basin

Volumetric Rate	400	gpm
	77005.3	cu ft/day
Area	154,000	sq ft
Velocity or Linear Rate	5.00E-01	ft/day

Recharge from Precipitation

Rate	13	in/year
	2.97E-03	ft/day

Ratio of Infiltration Rate to Recharge	168.5

Vertical Recharge to Model

Area	344,000,000	sq feet
Recharge Flux	1.02E+06	cu ft/day
	5304	gpm

Horizontal Groundwater Movement

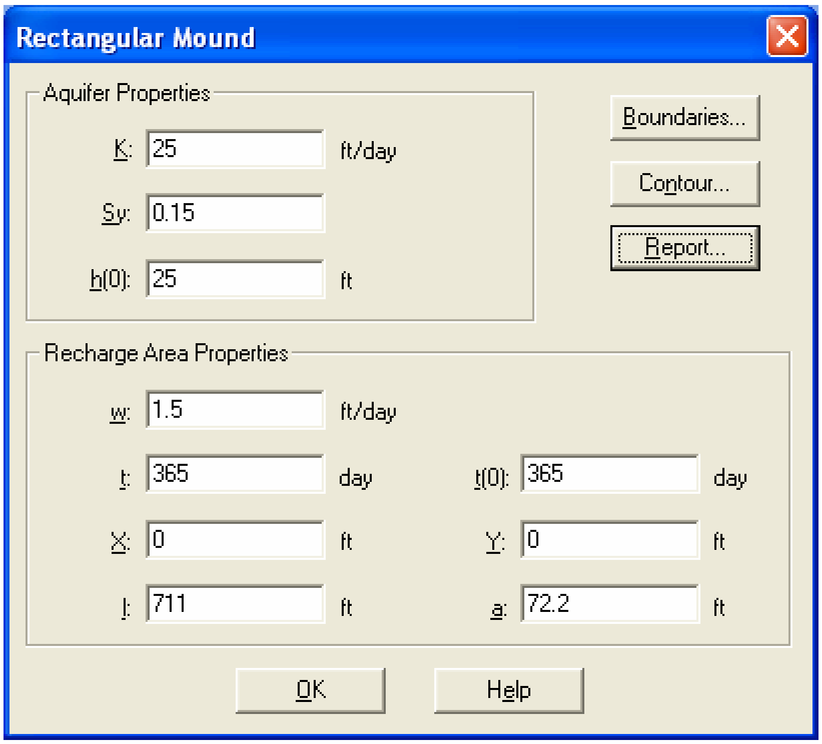
Length	21,500	ft
Height (combined average)	100	ft
Gradient	0.01	ft/ft
Hydraulic Conductivity	30	ft/day
Lateral Flow Rate	645,000	cu ft/day
	3350	gpm

Ratio of Vertical to Horizontal Flux	1.6

Attachment C

Analytical Calculations using AQTESOLV.

Scenario 1



Model input to AQTESOLV, Scenario 1

```
Transient Water-Table Rise Beneath a Rectangular Recharge Area

Groundwater Mounding Solution by Hantush (1967)


Aquifer Properties:

      Hydraulic conductivity, K = 25 ft/day

      Specific yield, Sy = 0.15
```

Initial saturated thickness, h(0) = 25 ft

Recharge Area Properties:

Recharge rate, w = 1.5 ft/day

Simulation time, t = 365 day

Time when recharge stops, t(0) = 365 day

X coordinate at center of recharge area, X = 0 ft

Y coordinate at center of recharge area, Y = 0 ft

Length in x direction, l = 711 ft

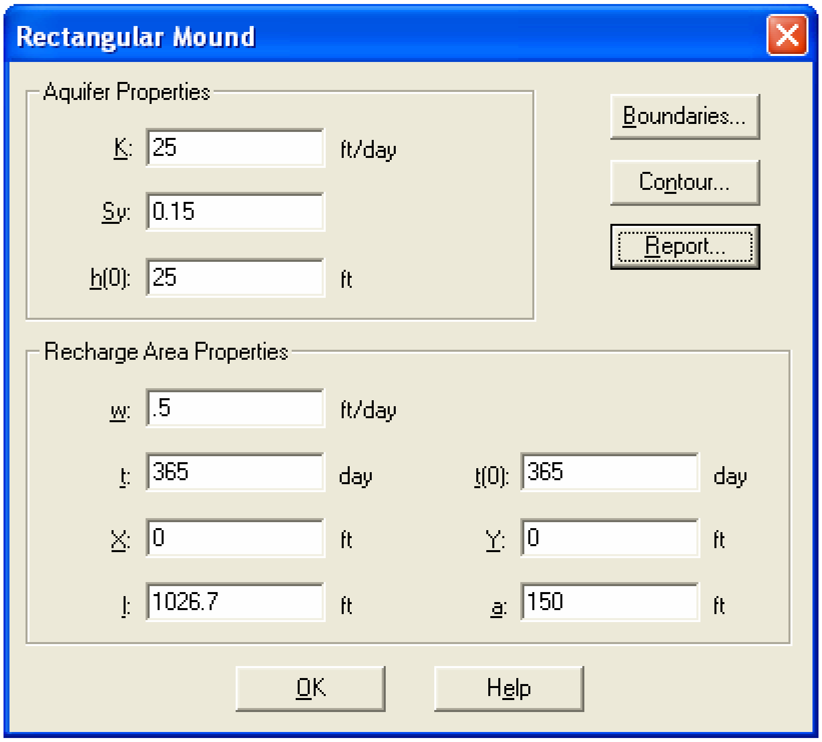
Length in y direction, a = 72.2 ft

Water-Table Rise at Center of Recharge Area:

t (day)	h (ft)
36.5	22.1065
73	25.701
109.5	27.7094
146	29.0929
182.5	30.1432
219	30.9869
255.5	31.6905
292	32.2929
328.5	32.819
365	33.2855

Report generated by AQTESOLV v4.50.002 (www.aqtesolv.com) on 04/08/08 at 08:06:37.

Scenario 2



Model input parameters to AQTESOLV, Scenario 2

```
Transient Water-Table Rise Beneath a Rectangular Recharge Area

Groundwater Mounding Solution by Hantush (1967)


Aquifer Properties:

      Hydraulic conductivity, K = 25 ft/day

      Specific yield, Sy = 0.15

      Initial saturated thickness, h(0) = 25 ft


Recharge Area Properties:

      Recharge rate, w = 0.5 ft/day
```

Simulation time, t = 365 day

Time when recharge stops, t(0) = 365 day

X coordinate at center of recharge area, X = 0 ft

Y coordinate at center of recharge area, Y = 0 ft

Length in x direction, l = 1026.7 ft

Length in y direction, a = 150 ft

Water-Table Rise at Center of Recharge Area:

t (day)	h (ft)
36.5	17.6971
73	21.5131
109.5	23.6638
146	25.1472
182.5	26.273
219	27.1769
255.5	27.9301
292	28.5745
328.5	29.1368
365	29.635

Report generated by AQTESOLV v4.50.002 (www.aqtesolv.com) on 04/08/08 at 08:04:59.

End

Attachment D

Foth & Van Dyke Memo, January 11, 2006

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)

Attachment E

Table 1. Wells, borings, and associated data

Site Number	GW Chemistry Data	Log	General Location	Infiltration test	Soil boring or Seep piezometer
QAL 001A/D			Just N of Eagle Project		
QAL 002 A/D			NW of Eagle Project		
QAL 003 A/B			Just W of Eagle Project		
QAL 004 A/D	X		S of Eagle Project		
QAL 005 A/D	X		SW of Eagle Project		
QAL 006 A/B	X		SE of Eagle Project		
QAL 007 A/D			Far NW of Eagle Project		
QAL 008 A/D	X		NE corner of Eagle Project		
QAL 009 A/D	X		E of Eagle Project		
QAL 010 A			Far SE of Eagle Project		
QAL 015 -019			E-NE of project area		Seep piezometers
QAL 020			N of project area		Seep piezometer
QAL 021			N-NW of project area		Seep piezometer
QAL 022			Far NW of project area		Seep piezometer
QAL 023B			West half of project area, over ore body		
QAL 024A		X	West half of project area		
QAL 025A		X	Center of project area		
QAL 026A		X	North center of project area		
QAL 027A		X	East half of project area		
QAL 028A		X	East half of project area		
QAL 029A/D		X	East half of project area, close		

Site Number	**GW Chemistry Data**	**Log**	**General Location**	**Infiltration test**	**Soil boring or Seep piezometer**
			to outcrop		
QAL 030		X			Soil boring
QAL 031D	X (1 date)	X	Eastern border of project area	X	
QAL 032		X	Within project area		Soil boring
QAL 033		X	Within project area		Soil boring
QAL 034		X	Within project area		Soil boring
QAL 035		X	Within project area		Soil boring
QAL 036		X	Proposed discharge area	X	Soil boring
QAL 037		X	Proposed discharge area	X	Soil boring
QAL 038		X	Proposed discharge area	X	Soil boring
QAL 039		X	Proposed discharge area	X	Soil boring
QAL 040		X	Proposed discharge area	X	Soil boring
QAL 041D		X	Eastern border of project area		
QAL 042		X	Proposed discharge area	X	Soil boring
QAL 043B		X	Western part of project area, near ore body		
QAL 044B		X	Western part of project area, near ore body		