Hydrogeology of the Proposed Crown Jewel Open Pit Gold Mine, Okanogan County, Washington, USA

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ABSTRACT

The Crown Jewel mine is a proposed open pit gold mine by Battle Mountain Gold that would be located near Chesaw in Okanogan County, Washington. The mine site hydrology has been characterized by numerous methods including stream gauging, drilling of mineral exploration holes, piezometers, monitoring wells, packer tests, and pumping tests. Pumping tests and packer tests were used to investigate the hydraulic behavior of the groundwater flow system and in particular the behavior of the North Lookout Fault zone, a prominent structural feature that crosses the site. The overall conceptual model of the hydrogeology of the site was investigated through numerical modeling. Two dimensional cross-sectional modeling (SEEP/W) and two-dimensional plan view modeling was used to evaluate the effect of pit dewatering on groundwater and surface water conditions.

KEY WORDS

Hydrogeology, Dewatering, Models, Pump Test

INTRODUCTION

Battle Mountain Gold Company proposes to mine the Crown Jewel orebody located about 250 miles (400 km) south east of Vancouver, British Columbia. The orebody contains an estimated mineable resource of about 1.5 million ounces of gold.

The proposed Crown Jewel pit covers an area of approximately 120 acres (0.5 km^2), and is located near the top of Buckhorn Mountain at an elevation of about 5,500 feet. The pit will be mined to an elevation of 4,505 feet amsl (above mean sea level), which is up to approximately 450 feet (140 m) below the groundwater level on Buckhorn Mountain. The pit will be mined over a period of about 9 years to final pit-bottom elevations ranging from 4,505 to 4,900 feet amsl. The deepest section of the pit will occur in the northern pit area, while the southern part of the pit will only be mined to an elevation of about 4,920 feet amsl.

The purpose of this paper is to present a summary of the investigations used to evaluate the hydrogeological conditions at the mine site, and to develop the hydrogeological conceptual model. Based on the conceptual model, various approaches for estimating groundwater inflows to the open pit, and changes in local groundwater levels due to mining are presented.

PHYSICAL CONDITIONS

Setting

The proposed pit is located on the eastern flank near the top of Buckhorn Mountain, where elevations vary from about 4,950 to over 5,500 feet amsl. Buckhorn Mountain is elongated to the north and south, and is flanked on the east and west by steeply dipping topography. To the east, the topography eventually begins to flatten towards the headwaters of Marias and Nicholson Creeks, which drain eastward to Toroda Creek.

Buckhorn Mountain in the vicinity of the proposed pit is drained by Gold Creek, Bolster Creek, and Ethel Creek to the west and by Nicholson Creek and Marias Creek to the east. Streamflow monitoring stations are located along these creeks. Streamflow data have been collected over several years to assist in the development of a site-wide water balance.

Climate

The climate of the site is classified as cool temperate with cold snowy winters and cool wet summers. Average January temperatures are about 20F (-6C). Average July temperatures are about 60F (15C). The average annual precipitation at the site is 20 in. (500 mm), of which snowfall yields about 6 in. (150 mm) of water. The average annual pan evaporation for the site is about 38 in. (965 mm), ranging from about 7.5 in. (190 mm) in July to 0.5 in. (12 mm) in December and January. Annual potential evapotranspiration is about 24 in. (610 mm).

Geology

The mine site lies within the western margin of the Eocene-aged Toroda Creek Graben, and on the northern edge of the Okanogan Metamorphic Core Complex. The rocks within the region are generally accreted Permian to Triassic-aged island-arc volcanics and clastics. The stratigraphy in the proposed pit area consists of the Permo-Triassic Brooklyn Formation, which is made up of an upper meta-volcanic group and lower meta-sedimentary group. The upper group consists of andesite that is exposed at higher elevations in the southern pit area. The lower group (meta-sedimentary) consists of marble, hornfels, silicified conglomerate, silicified fine-grained clastics, and silicified volcaniclastics.

The Eocene-aged, granodiorite Buckhorn Mountain pluton underlies the lower group of the Brooklyn Formation in the north-central portion of the pit. Numerous dikes and sills consisting of granodiorite, diorite, rhyolite, quartz porphyry, biotite porphyry and feldspar porphyry also occur in the Brooklyn Formation in the vicinity of the proposed pit.

At the site, the most prominent structural feature is the North Lookout Fault zone, which crosses the proposed pit from southwest to northeast. The fault strikes N45E and dips from 60 to 70 degrees to the southeast. The fault zone widens from approximately 75 feet (23 m) in the southwest corner of the pit to as much as 200 feet (60 m) near the northeastern margin of the pit (Gold Bowl area). The pumping test of the North Lookout Fault zone (described later) indicates that it is not more permeable than the surrounding rock.

Smaller faults and fractures have been identified from corehole logs. Average fault and fracture spacing, based on 58 corehole logs, is between 16 and 43 in (0.4 m to 1.1 m). For hydrogeologic purposes this can be considered to represent a relatively high degree of fracturing. Core logs indicate that clay alteration associated with most of these faults and fractures is relatively minor, and that they are primarily brittle structures characterized by highly fractured rock rather than by clay-altered or gouge material. Many of these faults and fractures strike to the northeast and dip steeply to the southeast, but other orientations and dips are not uncommon.

Groundwater Elevations and Directions of Flow

Recharge to the groundwater system originates as precipitation and snowmelt over the higher elevations of Buckhorn Mountain, with groundwater generally flowing from the higher elevations to the lower elevations. Groundwater on the eastern side of Buckhorn Mountain generally flows in an easterly direction toward Marias Creek and Nicholson Creek (and ultimately Toroda Creek). On the western side of Buckhorn Mountain, groundwater movement is generally in a westerly direction toward Bolster Creek, Gold Creek, and Ethel Creek (and ultimately Myers Creek). (Figure 1).

A steep water table gradient exists on Buckhorn Mountain, reflecting the steep topography and relatively low permeability of the bedrock. Groundwater moving downward within the bedrock on Buckhorn Mountain locally discharges as baseflow to the tributary creeks which drain the mountain, or percolates downward to a regional flow system which likely eventually discharges to the alluvium in the Myers Creek Valley or the Toroda Creek Valley (Figure 2).

There is a considerable vertical groundwater flow component throughout much of the proposed pit area. In general, the vertical component of groundwater flow is directed downward in the higher elevated terrain in the west and south, and upward in the lower elevations in the northeastern portion of the pit.

Groundwater elevations typically mimic the ground surface elevations in a subdued fashion: groundwater elevations are highest where ground surface elevations are highest, and lowest where ground surface elevations are lowest. Anomalously low groundwater elevations occur in the east-central portion of the proposed pit, primarily southeast of the North Lookout Fault zone. Evidence suggests that the low groundwater elevations are because the North Lookout Fault may be less permeable than the surrounding rock and may act as a hydraulic barrier to groundwater flow.

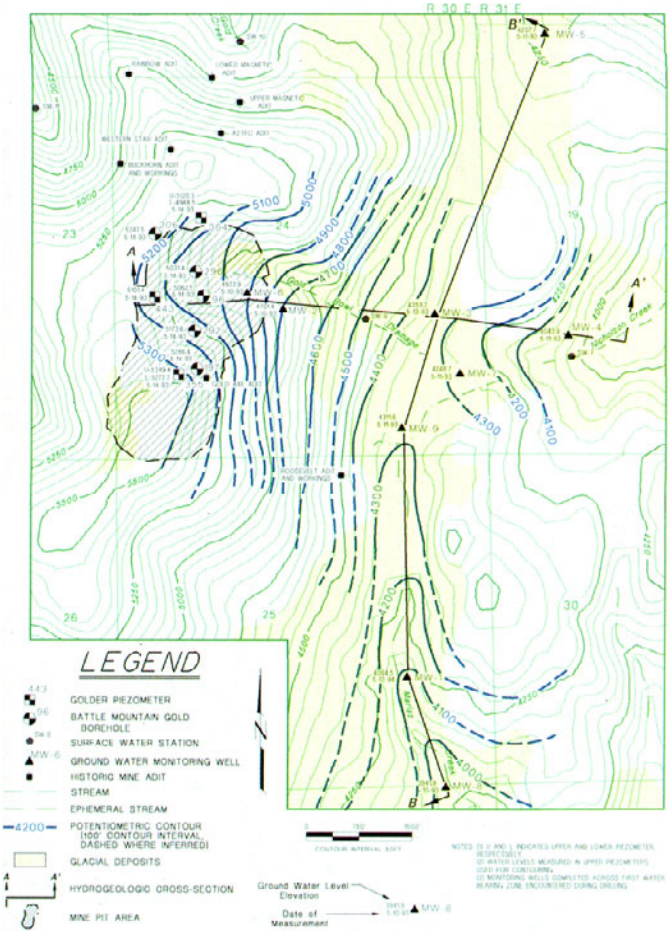

Figure 1

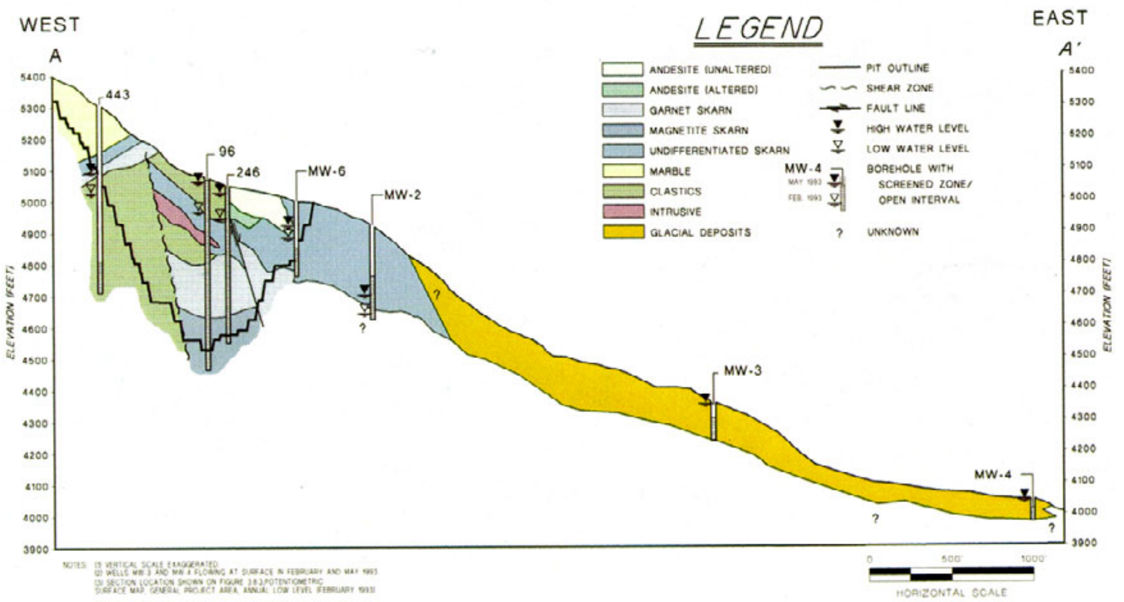

Figure 2

Groundwater levels in bedrock respond rapidly to recharge as evidenced by water level changes of over 100 feet (30 m) during the spring runoff period. Water levels rise rapidly in

April and May reaching a peak and then decline for the remainder of the year (Figure 3). Water levels in wells in the unconsolidated deposits respond in a much subdued manner to recharge. The contrast in water level response in wells in bedrock and the unconsolidated deposits is a function of the storativity and permeability of the units.

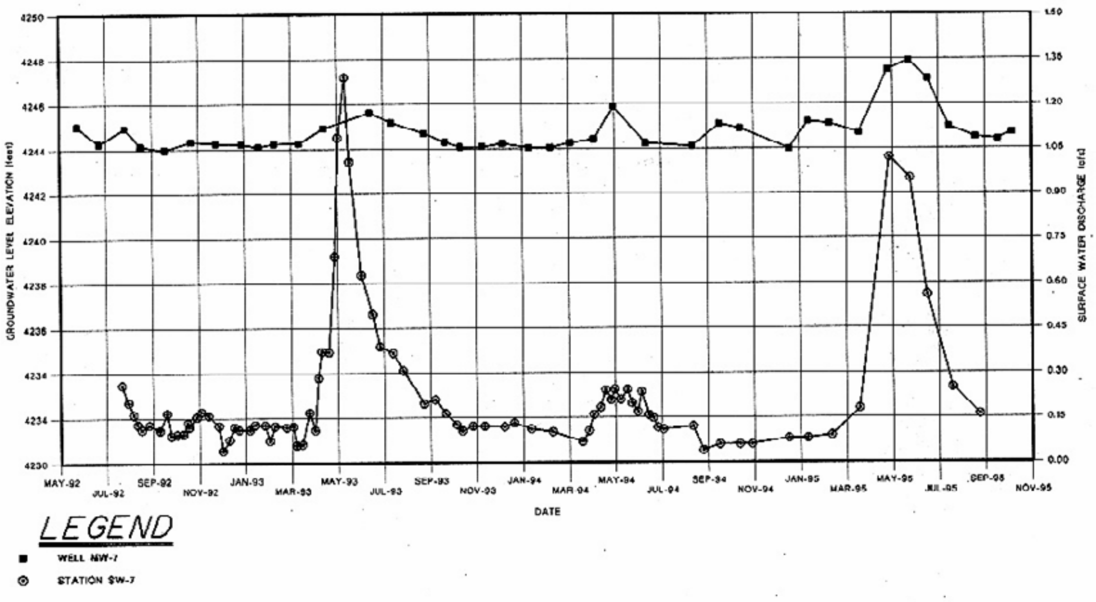

Figure 3

HYDROGEOLOGIC INVESTIGATION AND ANALYSIS TECHNIQUES

Pump Test

A pumping test was carried out in one modified exploration hole (90-239) that intersected the North Lookout fault zone. The purpose of the test was to determine the hydraulic characteristics of the fault zone and its relationship to the bedrock groundwater flow system. The well was pumped for 11 days at a rate of 20 USgpm (1.25 L/s)with several piezometers and streamflow gauges used to measure the effect of pumping. For our analysis of the test, it was assumed that the fractured rock behaved like an equivalent porous media. This assumption was made because of the high fracture frequency (Freeze and Cherry, 1979 and Nordqvist, et al,1992). This approach of representing fractured rock as an equivalent porous media has commonly been used in the past to interpret pumping tests (Gale, 1982, and Long et al, 1982).

Since the purpose of this study was associated with determining the magnitude of groundwater inflows into the proposed pit, the continuum approach was believed to be the most appropriate because:

1) The zone of influence of the proposed pit is large in comparison to the scale of faulting and fracturing that occurs within the rock mass. As such, the faults and fractures are interconnected well enough on this scale to behave as a continuum; and

2) Water-level data indicated that the faults and fractures, in general, are interconnected sufficiently to rapidly transmit water-level changes throughout the system in a fashion analogous to that of a porous medium.

The pump test was analyzed using an approach proposed by Vandenberg, 1977), which provides an estimate of the range of average transmissivity and storativity, by bracketing the data from all of the piezometers plotted on a logarithmic scale between two Theis type curves (drawdown data plotted versus time divided by the radial distance squared). Butler, et al, (1993), Naff (1991) and Oliver (1993) , along with previous works, further suggest that the rate of water level declines observed during late times, or the rate of water level declines observed from piezometers located at greater distances from the pumping well reflect the bulk average hydraulic properties of the aquifer. The magnitude of drawdown observed at different locations within a heterogeneous aquifer may differ in response to the heterogeneities, but the rate of change of the drawdown is generally consistent with the average aquifer properties (Oliver, 1993). The result of these findings is simply that the conventional classical methods of pumping test analysis (particularly the Jacob method) can be used, with appropriate caution, to provide estimates of the average hydraulic characteristics of heterogeneous systems.

A four-step approach was used to analyze the pumping test data:

Step 1 The data were plotted on a logarithmic and semi-logarithmic scale, and the drawdown response of each piezometer (and the pumping well) was carefully evaluated and compared with the Theis curve as a reference;

Step 2 Based on the general character of the drawdown responses identified in Step 1, and on an evaluation of possible dual-porosity behavior, the appropriate methods for evaluating the hydraulic characteristics of the rock mass were selected;

Step 3 Following selection of the appropriate pumping test analysis methods, the drawdown responses noted for each piezometer (and the pumping well) in Step 1 were evaluated qualitatively to determine the general characteristics of the rock mass (i.e. relative permeability of the North Lookout Fault zone, leakage, recharge, and boundary conditions); and

Step 4 The pumping test analysis methods were applied to provide an estimate of the hydraulic properties (transmissivity and storativity) of the rock.

This approach to analyzing the pumping test provides a good understanding of the overall hydrogeologic characteristics of the site. However, due to the idealized assumptions inherent in the pumping test analysis methods, the average rock hydraulic properties at the site can only be determined within a certain range. Most pumping test analysis methods are based on the assumption that the aquifer is homogeneous, isotropic, uniform in thickness, and of infinite horizontal extent. Furthermore, the potentiometric surface is assumed to be flat, and flow is assumed to be horizontal. These conditions are rarely met in practice, and most of the basic assumptions are violated to some degree at the Crown Jewel site.

Evaluation of Appropriate Pump Test Analysis Method

In order to determine which pumping test analysis method(s) should be used to evaluate the hydraulic characteristics of the rock mass, the general character of groundwater flow to the pumping well was determined. To make this determination, the logarithmic drawdown data were examined for distinctive features indicative of linear and radial flow to the pumping well. (Figure 4) If flow to the pumping well is radial, the data collected from the piezometers will plot on a logarithmic scale in a fashion consistent with the Theis type curve. In this case, the classical Theis and Jacob methods of analysis used for porous media are appropriate (assuming that dual-porosity effects are negligible). If the flow is linear, the data from piezometers installed within the same fracture would plot as a straight line on a logarithmic scale with a characteristic slope of 0.5. In this case, a single fracture model may be appropriate for pump test analysis.

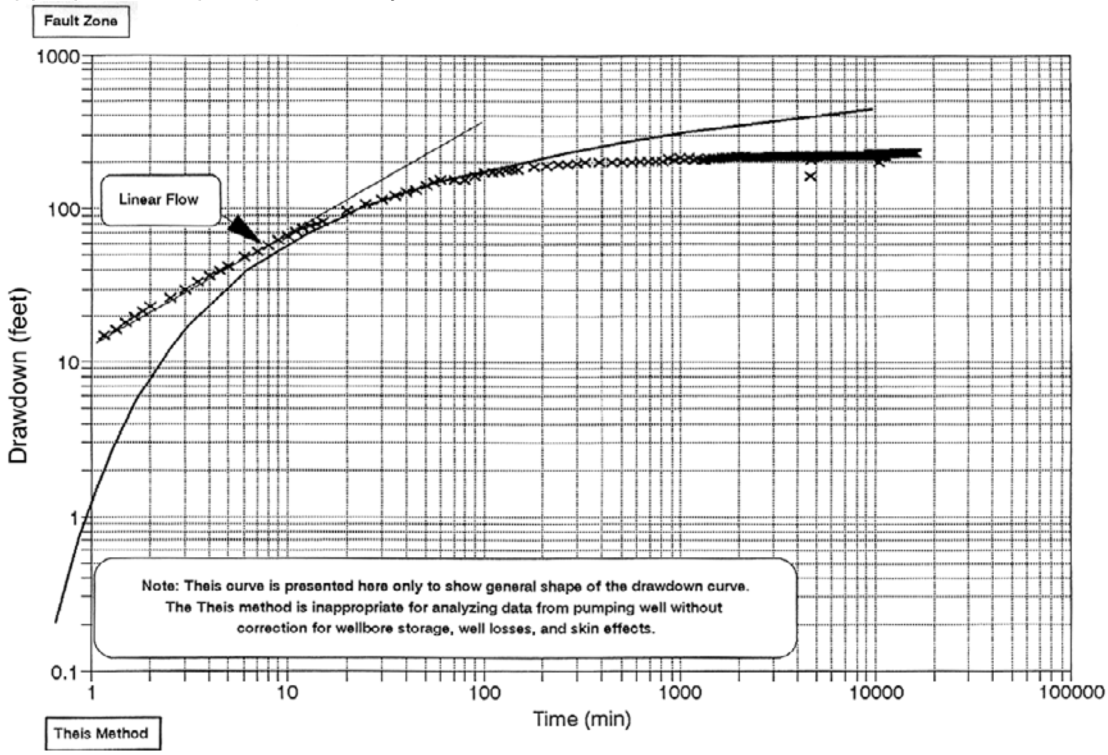

Figure 4

The data from the piezometers were further analyzed to determine if the application of "dual-porosity" models would be appropriate. In dual-porosity models, the early time data would plot on the Theis type curve; the mid-time data would flatten considerably; and the late-time data again would fall on the Theis type curve.

Overall, data from seven of the eleven piezometers plotted on a logarithmic scale in a fashion consistent with the Theis type curve (Figure 5), indicating that flow to the pumping well is generally radial to quasi-radial. Drawdown observed at the remaining piezometers was insufficient for analysis. Furthermore, the three-armed signature of dual-porosity behavior was not evident from any of the piezometers. From this analysis, the rock mass is interpreted to generally behave as a heterogeneous continuum, and the matrix porosity appears to be negligible. As such, the conventional pumping test analysis methods were deemed applicable.

Evaluation of General Hydrogeologic Characteristics

Permeability of North Lookout Fault Zone

Based on the drawdown data collected from the piezometers, the flow to the well was radial to quasi-radial (except in the immediate vicinity of the pumping well), and no no-flow boundary effects were observed. As such, there was no evidence that the North Lookout Fault zone was significantly more permeable than the surrounding rock mass. Furthermore, as illustrated in Figure 6, the drawdown response to pumping observed in piezometers installed within the fault zone was generally significantly slower than the drawdown response observed in the piezometers installed in the northwest fault block. In addition, the decrease in slope of the drawdown data (plotted on a semi-logarithmic scale) observed in the pumping well, and the nearby piezometers 90-245 and 90-238L is indicative of the drawdown cone expanding from a zone of lower permeability into a zone of higher permeability. This evidence suggests that the North Lookout Fault zone may be less permeable than the surrounding rock mass.

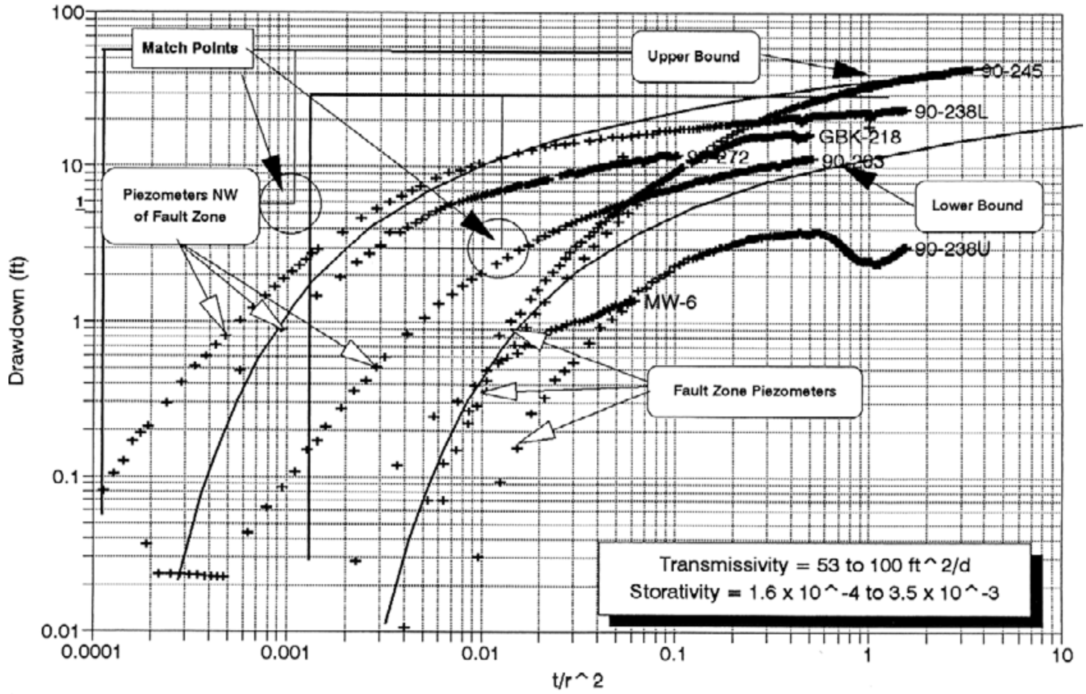

Figure 5

Leakage, Recharge, and No-flow Boundaries

With the exception of the water-level response observed in the pumping well, the drawdown behavior was generally consistent with the theoretical Theis response for a confined aquifer with an areal extent greater than the area of influence of the pump test. There was no evidence of leakage, or the presence of recharge or no-flow boundaries within the area of influence of the pumping test.

Water levels in the two piezometers, 91-456 and GAC-188, located southeast of the fault zone did not respond to pumping. This would be consistent with the rock mass on the southeast side of the fault zone being lower in permeability than the fault zone and the rock mass to the northwest of the fault zone. The data collected from the piezometers within and northwest of the fault zone, however, showed no boundary condition effects corresponding with this scenario.

Rock Mass Heterogeneities

The rock mass at the proposed Crown Jewel site is undoubtedly heterogeneous, particularly on the small scale due to differences in fault/fracture patterns and frequencies. The variation in early-time drawdown responses illustrates this point. This early-time pumping test data provides some indication that the North Lookout Fault zone may be somewhat less permeable than the surrounding rock mass. The variable drawdown at different locations in the vicinity of the pumping well, as shown in Figure 6, further illustrates the heterogeneous character of the rock mass.

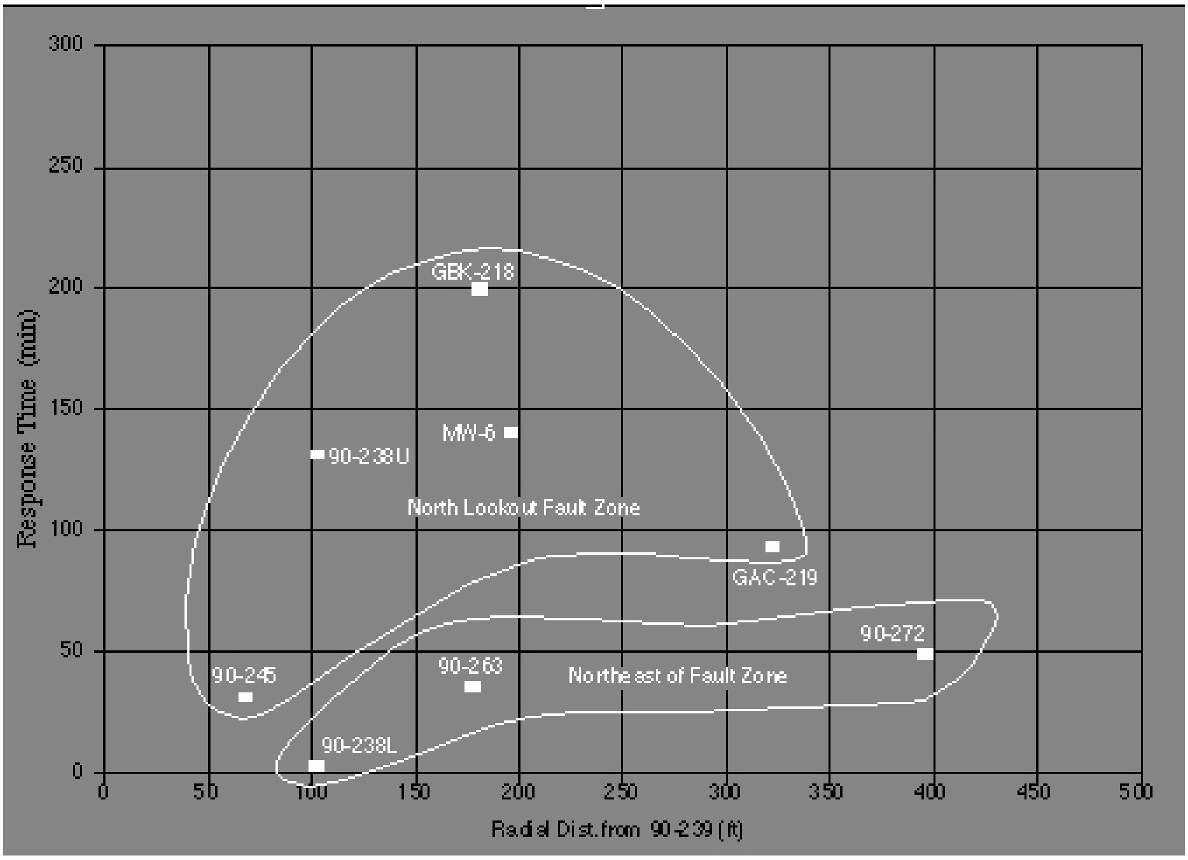

Figure 6

The average properties of the rock mass will, in part, control the short-term rates of groundwater inflows into the proposed pit. In other words, the short-term rates of groundwater inflows in the proposed pit will be governed by the cumulative rates of inflow from all of the faults and fractures contributing flow to the pit. The conventional methods of pumping test analysis can be applied to late-time data, or to data collected from piezometers located at distance from the pumping well to provide estimates of the average aquifer characteristics.

Anisotropic Character of the Rock Mass

Due to the prominent nature of faults and fractures oriented northeast-southwest, the rock mass, as a whole, could possibly be anisotropic with the highest permeability oriented northeast-southwest. Other structures, however, are oriented to the northwest-southeast. Under ideal conditions, pumping test analysis methods exist to determine anisotropy. At the Crown Jewel site, the heterogeneous nature of the rock mass likely overshadows any anisotropic characteristics that may otherwise be manifested in the pumping test data.

Average Rock Mass Hydraulic Properties

The Theis curve matching method, the Jacob method, and the Theis Recovery method were used where appropriate to estimate aquifer properties. In addition, the Vandenberg method was used to provide an estimate of the range of the hydraulic properties. More weight was given to late-time data, due to the heterogeneous character of the rock mass.

The results of the Vandenberg method, which takes the data collected from all of the piezometers into account (with the exception of those that did not respond during pumping), suggests that the average rock hydraulic conductivity is between 0.13 and 0.25 ft/day (4.6×10^{-5} cm/s to 8.8×10^{-5} cm/s) (assuming an aquifer thickness of 400 feet (122 m), equivalent to the pre-pumping test saturated thickness in the pumping well), and the average storativity is between 1.6×10^{-4} and 3.5×10^{-3}.

Analysis of the drawdown and recovery data collected from individual piezometers yielded a somewhat wider range of estimates of transmissivity and storativity. For example, hydraulic conductivities of between 0.05 and 1.48 ft/day (1.8×10^{-5} and 5.2×10^{-4} cm/s) were calculated. Estimates of storativity calculated from the drawdown observed at the piezometer ranges from 1.0×10^{-4} to 2.7×10^{-3}.

From these results, we estimate that the average rock hydraulic conductivity of the rock mass is likely between about 0.1 and 0.75 ft/day (3.5×10^{-5} and 2.6×10^{-4} cm/s), and that the average storativity is conservatively estimated at between 1×10^{-3} and 5×10^{-3}.

Connection between Groundwater and Surface Water

During the pumping test, six streams and two adits were monitored to determine the effects of pumping on surface water flow rates. Most of the sites show a general regional trend of declining stream flow associated with seasonal declining base flow. Streamflow at one station diminished in response to pumping. The station is located about 1,500 feet (460 m) east of the pumping well, along Gold Bowl creek, which drains the northeastern corner area of the proposed pit. The stream surfaces in the northeastern corner of the proposed pit, approximately 600 feet (180 m) northeast of the pumping well. Prior to pumping, the stream flow at SW-9 was approximately 41 USgpm (2.6 L/s). Within 24 hours of pumping, stream flow had decreased by about 10 USgpm to 31 USgpm (0.62 to 1.9 L/s). Stream flow continued to decline throughout the test until by the end of the pumping test, stream flow was about 11 USgpm (0.69). This is approximately 30 USgpm (1.9 L/s) less than at the beginning of the test. Within approximately 16 hours after pumping ceased, the flow rate had increased by about 4 to 5 USgpm (0.25 to 0.31 L/s).

Part of the observed decline in stream flow is associated with the regional seasonal decline, as obviously a pumping test at a rate of 20 USgpm (1.25 L/s) cannot on its own reduce the surface water flow rate by 30 USgpm (1.9 L/s). It appears that pumping reduced the stream flow by about 14 USgpm (0.87 L/s). The relatively rapid response of pumping observed at SW-9 illustrates that the groundwater system (which includes natural discharge to local surface water bodies) responds rapidly to perturbations, due to its generally relatively high fracture interconnections and low effective porosity.

Packer Testing

Packer testing was used to provide information on the vertical distribution of hydraulic conductivity with depth, and to determine the hydraulic conductivity of the North Lookout fault zone. The packer injection tests were performed in four boreholes (D90-43, D90-45, D91-101, D91-125) that ranged in depth from approximately 400 to 780 feet (120 to 240 m) below ground surface (bgs). Boreholes D90-43 and D91-101 intersected the North Lookout fault zone and Boreholes D90-45 and D91-125 were located northwest of the fault zone.

The packer system consisted of two packers on an NX sub attached to NX drill rods. Included with the packer assembly were three 0 to 750 pounds per square inch (psi) electronic pressure transducers (GeoKon Equipment) that monitored the water pressure above, below and between the packers. The packers could inflate to 5 inches (125 mm) in diameter and seal a 4-foot (1.2 m) section of the borehole. The packers were connected by a perforated pipe that resulted in a packer-test interval of either 12 or 23 feet (3.6 or 7.0 m).

The injection rate of water into the test section was measured using one of two in-line flow meters. The high flow meter (Trident, Inc.) was calibrated for flows greater than 0.1 USgpm (6.3×10^{-3} L/s) and a micro flow meter (Kobold Instruments) was calibrated for flows from 0.01 to 0.1 USgpm (6.3×10^{-4} to 6.3×10^{-3} L/s). Each test proceeded until it was determined that the flow rate and injection pressure reached relatively stable values (usually after 8 to 12 minutes). The injection pressure at the surface was initially 30 psi, and was occasionally increased to observe if flow was laminar or if turbulence was becoming a factor of the test.

A total of 77 packer injection tests were performed, including nine tests within the North Lookout fault zone. The tests were analyzed using methods presented in Hvorslev, (1951). The calculated hydraulic conductivities ranged from 10^{-4} ft/d to 10^{-1} ft/d (3.5×10^{-8} to 3.5×10^{-5} cm/s).

The range of hydraulic conductivities for the North Lookout fault zone was from 10^{-4} to 10^{-2} ft/d (3.5×10^{-5} cm/s to 3.5×10^{-3} cm/s). Although sections of the fault zone did have relatively high conductivities, there were similar high values measured in the hanging wall above the fault zone and immediately below the fault zone in the foot wall (Figure 7).

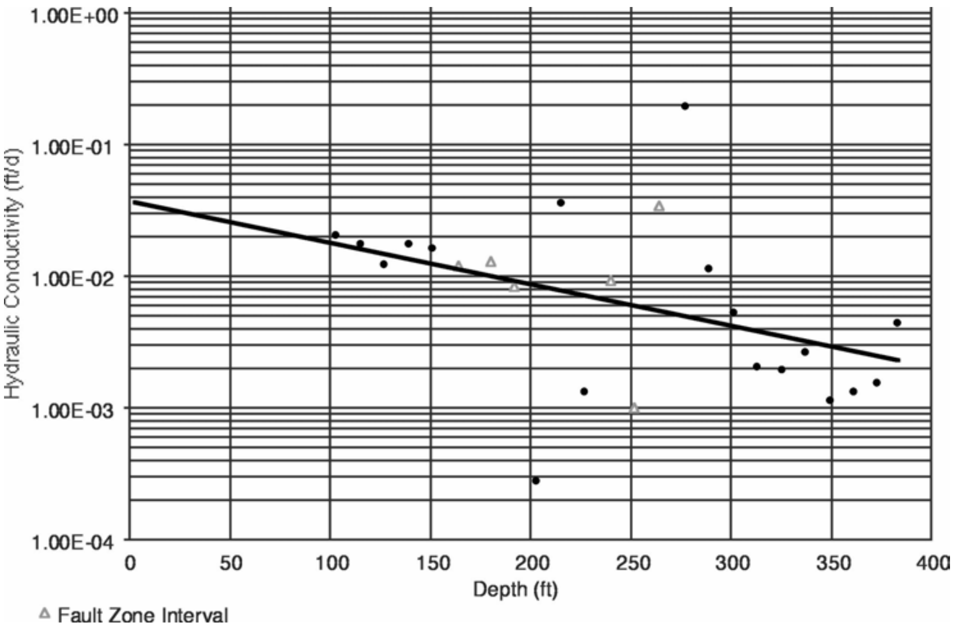

Figure 7

Streamflow Data

Streamflow data were used to provide an estimate of groundwater recharge and surface water runoff. Groundwater recharge is one of the two components of groundwater that will enter the pit during and after mining (the other being groundwater released from storage). Based on base flow analysis, groundwater recharge of between 2 and 4 inches (50 to 100 mm) was estimated.

HYDROGEOLOGICAL CONCEPTUAL MODEL OF CROWN JEWEL MINE

The hydrogeologic system at the proposed mine is controlled by the topographic setting of the proposed pit near the top of Buckhorn Mountain, the highest topographic feature present in the region. The topographic setting of the proposed pit makes it unique in that the quantity of water that can enter the pit can only originate from: 1) groundwater stored in the rock surrounding the pit; 2) from groundwater recharge occurring on Buckhorn Mountain in the immediate vicinity of the pit; and 3) from precipitation falling within the pit.

Key components of the conceptual model are:

- The permeability of the rock is relatively low (hydraulic conductivity estimated at between 0.1 and 0.75 ft/d [3.5×10^{-5} to 2.6×10^{-4} cm/s]), and is primarily associated with fractures and faults. Faults and fractures with spacing averaging between 16 and 43 inches (0.4 m to 1.1 m), provide conduits for groundwater flow. The North Lookout Fault zone is not more permeable than the surrounding rock mass, and as such, it will not act as a local drain increasing inflows into the proposed pit;

- The effective porosity of the rock mass is low (estimated at between 0.1 and 0.5 percent), and is primarily associated with fault and fracture porosity. The low effective porosity is consistent with the metamorphic history of the rock mass: the original pore spaces between sediment grains and crystals (matrix porosity) have been infilled by precipitation of other minerals or lost due to compaction of the rock mass;

- Groundwater movement in the vicinity of the proposed pit is influenced by the steep topography resulting in a three-dimensional flow system;

- Groundwater recharge on Buckhorn Mountain is estimated at between 1.5 and 6 inches (38 to 150 mm), based on measurements of the base flow from streams and adits draining the Buckhorn Mountain area and precipitation data; and

- Water-level measurements collected from several boreholes and piezometers illustrate that groundwater elevations respond rapidly to perturbations (such as recharge). This suggests that, although the bulk rock mass is of generally low permeability, individual fractures and faults are generally well interconnected, which, in combination with the low effective porosity, allows for the rapid transmission of water level changes throughout the proposed pit area.

GROUNDWATER MODELING

Groundwater modeling was performed using a number of different models to evaluate various issues raised during the environmental impact studies for the mine. Models were used to estimate groundwater inflows, to determine the potential capture zone for the open pit, to determine the potential impact on streamflow and to estimate drawdown in the pit slopes. Models used included:

Model	Purpose
Spreadsheet Water Budget	Estimate pit inflows
FLOWPATH	Size of pit capture zone
SEEP/W	Size of pit capture zone
ABCFEM	Size of pit capture zone and groundwater inflows

Water Budget Model

A spreadsheet-based water budget model was developed to estimate annual pit inflows from groundwater and precipitation and to estimate the rise in water levels and lake development in the pit upon the cessation of mining. The water budget method involves tracking the quantities of water entering and leaving the system. For example, sources of water entering the proposed pit will be direct precipitation, groundwater stored in the rock adjacent to the pit, groundwater stored within the mined rock itself, and groundwater recharge from precipitation. Based on the size and depth of the pit below the water table and the capture zone area of the pit, the ultimate inflows into the proposed pit were determined, assuming that the groundwater system responded relatively quickly to mining. The spreadsheet model was implemented in Excel with Crystal Ball to understand the uncertainty in inflows. A schematic representation of the spreadsheet model for pit inflows is shown in Figure 8.

The water-budget approach was considered a good tool to estimate inflows into the proposed Crown Jewel pit because:

1) The topographic setting limits the area of groundwater and surface-water intercepted by the pit to a relatively small area surrounding the pit, which considerably simplifies the determination of groundwater inflows to the pit;

2) Due to the low effective porosity of the rock and relatively high degree of fracture interconnection, groundwater levels respond rapidly to groundwater recharge and discharge, and, therefore, will also respond rapidly to mining; and

3) If the groundwater system does not respond as quickly as envisioned, the assumption used in the water-budget approach of rapid groundwater level response to mining provides a conservatively high estimate of inflows into the pit during mining. Therefore, this approach provides a conservatively high estimate of the ultimate quantity of water intercepted by the pit.

The model input parameters were determined from existing data. Probability distributions were applied to each input parameter to reflect uncertainty in the true value. For the estimate of the pit capture zone, FLOWPATH simulations were performed to develop a range of potential sizes for the capture zone. The water budget model provided a median estimate of pit inflows of about 75 USgpm (4.7 L/s) at Year 9 with groundwater inflows representing about 35 USgpm (2.2 L/s).

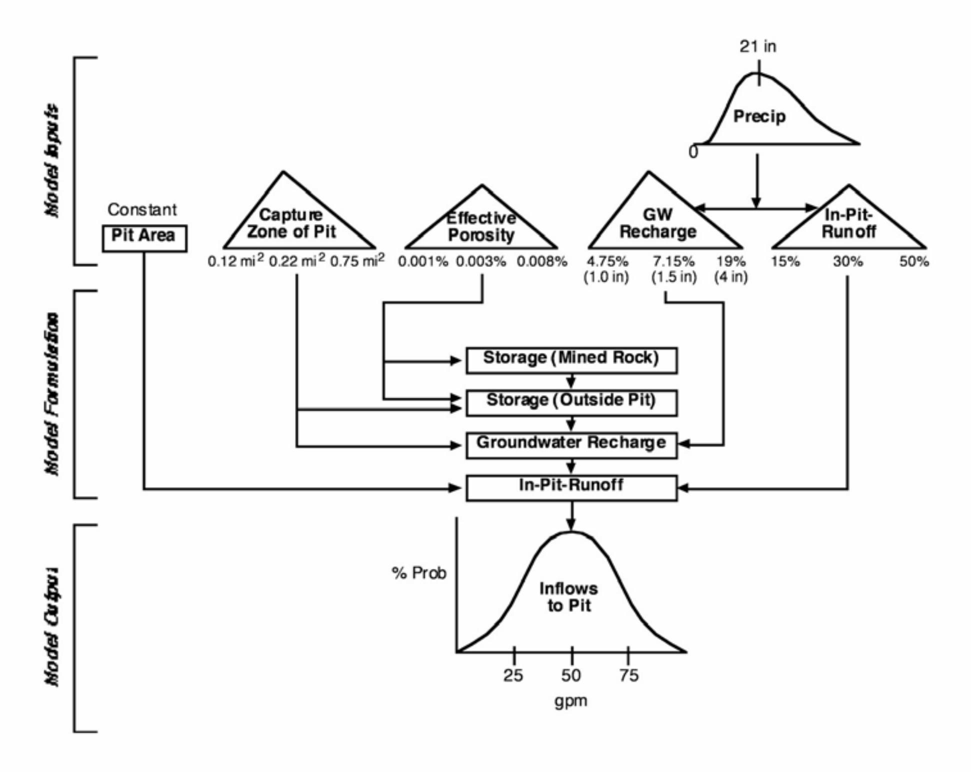

Figure 8

FLOWPATH Modeling

FLOWPATH (Franz and Guiger, 1992) is a two-dimensional numerical groundwater flow model capable of simulating confined, unconfined, and leaky aquifers. FLOWPATH includes a particle-tracking routine, which is based on a velocity interpolation and explicit time-stepping scheme, which can be used for estimating groundwater capture zones. The purpose of conducting the FLOWPATH simulations was to provide an estimate of the potential capture zone of the proposed pit, and to demonstrate some of the physical characteristics of the site. The modeling was not intended to provide preliminary estimates of pit inflows because of limitations in how FLOWPATH handles seepage face conditions.

The domain of the model consisted of an area approximately 3.75 miles (6 km) north-south by approximately 0.5 to 1 mile (0.8 to 1.6 km) east-west , which comprised most of the elevated terrain on Buckhorn Mountain. The perimeter of the model domain corresponds approximately to the topographic elevation of 4,500 feet amsl, which is approximately equal to the elevation of the bottom of the proposed pit (4,505 feet amsl). A constant head boundary condition (4,500 feet amsl) was applied to the model perimeter. The assumption applied is that the water table is at ground surface along the topographic elevation of 4,500 feet amsl. Constant head nodes were assigned to represent the proposed pit. The model domain was unconfined, with an infiltration rate (groundwater recharge rate) of 4-inches (100 mm) per year equally distributed over the model domain. A base elevation of 4,480 feet amsl was chosen for the model. Using a hydraulic conductivity of 0.02 ft/day (7 x 10^{-6} cm/s), a head distribution similar to that observed at the site was generated as a base case.

The two-dimensional model assumes that all groundwater leaves the system via the perimeter of the domain; no groundwater flows downward deeper into the mountain, as is likely the case for the three-dimensional flow system. The two-dimensional plan-view representation of a three-dimensional groundwater flow system, is therefore, an over-simplification of the groundwater system.

FLOWPATH was used to simulate the groundwater level configuration corresponding to the final pit configuration. The model predicted that groundwater levels would be lowered somewhat at distance from the pit, and would be lowered between 400 and 500 feet (120 and 150 m) in the north pit area, where pit elevations are lowest. In order to determine the capture zone area of the pit, a number of particles were placed at various distances around the pit, and a particle-tracking procedure was employed. The calculated capture zone area of the pit (area outside of pit boundaries) is approximately 0.22 square miles (0.56 km^2). Under this scenario pit inflows are about 34 USgpm (2.1 L/s).

Sensitivity analyses indicated that at greater hydraulic conductivities the model predicted groundwater elevations which were much lower throughout the model domain than thoseobserved, but that the size of the capture zone remained unchanged. Similarly, at lower conductivities, the model predicted much higher groundwater elevations throughout the model domain, but the size of the capture zone was unchanged. This indicated that the steady-state behavior of the site is primarily controlled by topography and not the hydraulic conductivity of the bedrock. The conclusion of the modeling is that the pit will intercept a specific percentage of flow originating as recharge on the mountain, regardless of the average hydraulic conductivity of the rock.

SEEP/W Modeling

SEEP/W (GeoSlope International, 1995) is a two-dimensional finite element groundwater flow model capable of simulating saturated and unsaturated flow conditions. SEEP/W was used to evaluate two-dimensional vertical slices through the pit area and to determine the approximate location of the groundwater capture zones along a limited number of vertical slices through the proposed pit.

The model was calibrated using hydraulic conductivity values from packer testing. These measurements showed a decrease in hydraulic conductivity with depth (Figure 7). Hydraulic heads for boundary conditions were taken from groundwater level measurements at the site. Infiltration was determined based on the baseflow analysis.

Modeling indicated that the size of the pit capture zone is a function of the hydraulic conductivity profile. With a rapid decrease in hydraulic conductivity with depth, the capture zone is very close to the pit. In this case, most groundwater flow occurs in a relatively shallow “skin” that is draped over mountainous terrain. With a more uniform vertical hydraulic conductivity profile, the capture zone is larger due to the greater thickness of the water transmitting zone. This allows groundwater levels to drop a greater amount and the groundwater divide to shift farther from the pit. If it is assumed that there is no vertical change in hydraulic conductivity, then water levels drop below the base of the pit and the pit no longer intercepts groundwater flow.

The overall conclusion from the SEEP/W modeling was that:

- A trend of decreasing permeability with depth must be present at the site to account for the observed groundwater levels;

- A small capture zone will develop around the pit when the pit is mined to its full depth, thus limiting impacts;

- Groundwater recharge is probably about 2 inches (50 mm) – this provides the best head calibration based on the packer test hydraulic conductivity data.

ABCFEM Model

ABCFEM (Brown and Hertzman, 1994) is a two-dimensional plan view finite element groundwater model that can incorporate depth variable hydraulic conductivity and can simulate the interaction of groundwater and surface water. The purpose of the ABCFEM model was to estimate the size of the capture zone that could develop around the pit and to estimate groundwater inflows during and post mining. The model was requested by the permitting agencies to provide assurance that the estimates developed using simpler models (water budget and FLOWPATH) were reasonable.

The ABCFEM model (HydroGeo Inc, 1996) was calibrated to observed water levels at several wells and springs based on an assumed recharge of about 4 inches (100 mm). Hydraulic conductivity was assumed to decrease with depth from 0.1 ft/day (3.5×10^{-5} cm/s) in the upper 200 feet (60 m) to 2.2×10^{-3} ft/d (7.7×10^{-7} cm/s) in the lower 800 feet of the model.

The model predicted a groundwater inflow of about 36 USgpm (2.25 L/s) in the final year of mining. This compared to an estimate of 35 USgpm (2.2 L/s) using the water balance spreadsheet approach. The model predicted that the shift in the groundwater divide beneath the topographic ridge west of the pit would be less than 300 feet (90 m). Again this result was consistent with the water budget, FLOWPATH and SEEP/W analysis.

CONCLUSIONS

This paper demonstrates a variety of modeling techniques that can be applied to the evaluation of groundwater impacts arising from mine dewatering. It is apparent, that under appropriate hydrogeological conditions, relatively simple models can be used providing the owner and regulators with reasonable confidence on the potential groundwater impacts.

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