DELINEATION OF GROUNDWATER CAPTURE ZONE FOR THE GRUM PIT, FARO MINE COMPLEX, YUKON TERRITORY

By

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Abstract
The groundwater flow system of the Grum waste rock dump was modeled using Visual MODFLOW. By modeling groundwater flow and conducting particle tracking of in the vicinity of the pit area, the Grum pit’s capture zone was delineated. Through desktop studies of previous technical reports conducted on the study area, boundary conditions and parameters were established and incorporated into the numerical model. The model was then calibrated through a number of simulated cases of different hydraulic conductivity distribution conditions. Sensitivity analyses were conducted to investigate the governing factors that may influence the capture zone geometry. The analyses conducted showed that the capture zone encompasses an area of approximately 14 km², and extends throughout the depth of the pit, where no deep regional flows were observed to bypass the pit. No flows from the opposite side of the Vangorda creek, where the Vangorda pit was located, crossed over to the Grum pit area. Analyses also showed that the capture zone geometry of the pit was largely governed by the hydraulic conductivity distributions and annual recharge rate.
Acknowledgements
I would like to show my gratitude to Dr. Leslie Smith for his support and guidance throughout
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1.0 Introduction
The Faro Mine Complex covers an area of approximately 25 km². The Faro Mine Complex consists of three distinct areas: the Faro Mine area, the Rose Creek Tailings Impoundment area, and the Vangorda and Grum open pit area. The mining complex was considered a world-class deposit of lead and zinc ores. Ore discovery and mine operation works began in the 1960s and terminated in 1998. The focus of this study, the Grum open pit area’s design dimension was set to be 1100 m long and 700 m wide. However, mining operations terminated before the pit reaches its intended design dimension. The Grum pit is surrounded by a waste rock dump of over 100 million tons of waste rocks. The construction of the Grum pit commenced in 1989 for ore removal by Curragh Inc. Mining operations was suspended in 1992 due to low metal pricing, and resumed in 1994 where proprietorship was transferred to Anvil Range Mining. Mining operations were completely terminated in 1998, where the maintenance works for the mining complex were transferred to the Federal Government. Planning of reclamation and closure thus begins. (Faro Mine Closure Office, 2009).

This thesis will investigate the groundwater flow pattern and outline the extent of the Grum pit’s capture zone. This thesis will covers a background investigation of the study area, literature reviews, an outline of the methods and modeling works conducted, and the acquired results from various simulated cases, which will investigate flow patterns under different pit permeability conditions. The thesis will also cover sensitivity analyses of governing parameters, and present a conclusion for the Grum pit’s capture zone boundary. The modeling works utilize the Visual MODFLOW software, base on the United States Geological Survey MODFLOW software.
2.0 Study Area Background

2.1 Location
The Faro Mine Complex is located north of Faro town, and approximately 200km Northeast of Whitehorse, in the Yukon Territory in the Anvil Range. The Faro Mine Complex is composed of three main areas: 1. The Faro Mine area, 2. The Rose Creek Tailings area, and 3. The Vangorda Plateau. The Grum pit study area is located within the Vangorda Plateau, which is consisted of two large open pits: the Grum pit and the Vangorda pit. Figure 1 and 2 below shows the Faro Mine Complex area and its location. The mining complex is located within close proximity to the traditional Kaska Nation territory and the traditional Selkirk First Nation territory.

Figure 1. The Faro Mine Complex: 1. Faro Mine area, 2. Rose Creek Tailings area, 3. Vangorda Plateau (Faro Mine Closure Office, 2009).
The concerned study area, the Grum pit, is located on a South facing slope dipping 6 to 12 degrees, north of Vangorda Creek and Dixon Creek. The pit is approximately 300 m away from the Vangorda Creek. The pit area also contains a small creek, the Grum Creek, which is connected to the Vangorda Creek. However, due to mining operations, the Grum creek was disconnected from the Vangorda Creek, and diverted to a water treatment plant. The pit itself is located north of the waste rock dump, separated by an access road. The detailed site plan can be viewed in Appendix I.

The study area can be located on the Online MapMaker provided by the Yukon Geological Survey (YGS) at approximately latitude 62° 15’ 31” and longitude 133° 13’ 2” as illustrated in Figure 3 below.
2.2 Geological and Geotechnical Background
The rock formation that makes up the majority of the study area is part of the late Pleistocene, McConnell Glaciations’ deposit, composed of a combination of glacial till and glaciofluvial sands and gravels. The host rock, the Vangorda Formation, is consisted mainly of unaltered non-calcareous and calcareous phyllites (SRK Consulting Engineers and Scientists, 2004). This poses as a problem as sulphides were generated together with the phyllite waste rocks from mining operations, which causes environmental concerns in the area. The predominant host rock in the Grum area is calcareous phyllite. The rock formation in the Grum area tends to be highly foliated. Several faults also exists within the Grum pit area (Robertson GeoConsultants Inc., 1996).
A reconnaissance investigation of the soil conditions was conducted by SRK in 2003. Test pits were used to gather information on subsurface soil conditions. From test pit investigations, it was revealed that there are some variations in the subsurface soil profiles interpreted for the Grum pit area. The west-end profile shows a 1 to 2 m layer of medium dense silty till overlying a fractured phyllitic bedrock, while no bedrock was discovered in the east end. The overlying soil profiles show high variations in soil conditions ranging from sands and gravel to silts and tills. The bedrock appears to be undulating with depths varying from 17 m below ground elevation to 40 m below ground elevation. The bedrock also appears to be undiscoverable in some areas. Non-phyllitic bedrock was also discovered at test pit SRK03-TP4 at depths of approximately 4 m. The detailed constructed soil profiles and test pits information is presented in Appendix II.

2.3 Hydrogeology
The study area is underlain mainly by late-Paleozoic age phyllitic bedrock, which does not contain any significantly sized aquifers in the vicinity. Regional groundwater flow is limited in the bedrock region as most flows could only occur through continuous fractures and fault zones. Flows within the bedrock may also be anisotropic due to the schistosity of the rock within the region. The significant portions of groundwater flow are then confined to the shallow aquifers from surface water recharge.

The geologic profiles showed that the study area is overlain by a more permeable glaciofluvial sands and gravels deposit, alternating with glacial tills and alluvial sediments. The paths of groundwater flows are then mostly controlled by the surface or bedrock topography, where subsurface flows would most likely be occurring at the interface between the bedrock and overburden deposits.
Ten boreholes were installed in 1996 across the whole Faro Mine Complex area to investigate groundwater conditions and behavior. In the Grum pit area, the unconfined, shallow aquifer was located in alluvial sands and gravels (Robertson GeoConsultants Inc., 1996), and was most likely hydraulically connected to nearby creeks. The surface aquifer was separated from a lower aquifer by a thin silt layer. Permeability tests were conducted to determine the hydraulic conductivity (K) values for each area. Rising and Falling-head slug tests were conducted to obtain an average value for bulk hydraulic conductivity. The bulk hydraulic conductivity values obtained from tests results range from $3 \times 10^{-6}$ m/s to $2 \times 10^{-3}$ m/s, where, due to testing setup, higher ranged values are most likely more accurate. Hydraulic conductivity values determined for the Grum pit study area within the colluvial sands and gravels deposit ranged from $8 \times 10^{-6}$ m/s to $2 \times 10^{-5}$ m/s (Robertson GeoConsultants Inc., 1996).

2.4 Climate
The Yukon Territory has a sub-arctic climate with temperatures ranging from -17.7°C in January and up to 14.1°C in July. The region is typically dry throughout the year with 50% of its annual precipitation being snow. The annual mean precipitation rate for the area is 267 mm (Government of Yukon, 2008), with mean annual evaporation rate of 139 mm (Janowicz, Hedstrom, & Granger, 2006). The mean precipitation rate is important to the study area as the groundwater flow system in the Grum pit area is mostly recharged at surface level with surface water flow confined within the overburden alluvial deposits.

3.0 Literature Review
No thorough investigations and studies of the Vangorda and Grum capture zone were previously conducted. Most investigations that took place were preliminary studies and reconnaissance investigations, where more thorough investigations were conducted in the Rose Creek and Faro
mine tailing areas due to higher concerns in those areas. Thus, limited information and data are available for the Grum and Vangorda pit areas, which makes the conducts of this paper difficult. However, several papers were discovered on groundwater flow modeling and capture zone delineation, although the geologic settings of the project may be unique to the area. The studies discussed in this section provide insights to the behavior of groundwater flows and capture zones, which are beneficial to the conduct of this thesis. These studies also provide further information on groundwater flow behaviors and capture zones that may be beyond the scope of this thesis.

3.1 Modeling of Groundwater Inflow to a Large Open-pit in Low-Permeability Mountainous Terrain

The Santa Rita Pit is an open pit copper mine located in Southwestern New Mexico. A three-dimensional groundwater flow model was developed using the MODFLOW-SURFACT software to outline the capture zone and the groundwater flow system associated with the pit.

The study area climate is semi-arid with a mean annual precipitation of 44 cm, and high evaporation rate of 191 cm. The study area lies within the San Vicente drainage basin. The study area shows late Cretaceous and Miocene intrusive activity, with major faults and dikes trending north-northeast. The rock formation present in this area includes intrusive and extrusive igneous rocks, marine sediments and continental deposits. The hydraulic conductivity shows low variations ranging from $3.5 \times 10^{-6}$ to $3.5 \times 10^{-4}$ cm/s, with alluvium deposit being more permeable than the range presented for other rocks. Volcanic rocks were also determined to be less permeable than other rocks on order of magnitudes of 10 to 100 times smaller. The author thus group different rock features together through their similarities in hydraulic conductivity range for simplicity in modeling works. The groundwater recharge sources were identified to be from infiltration of precipitation, stockpile seepage and reservoir seepage, with the major source
being infiltration from precipitation. Due to the study area being located in an area with low permeability, it was expected that the groundwater flow would be controlled by topography. Once the boundary conditions and conceptual model was defined, a steady-state model was constructed in MODFLOW-SURFACT, and the results were analyzed. Sensitivity analyses were also conducted to calibrate and improve the model further. The authors of this paper define the capture zone as the surface area in which the particles released at the water table would transport to the pit. From the results obtained, the authors note that at greater depth, groundwater flows are governed by the pit’s hydraulic sinks more so than the surface topography.

3.2 Capture Zone Geometry in a Fractured Carbonate Aquifer
The study investigates groundwater flow through a transitional fractured bedrock where the medium is divided into three depth zones. The upper depth zone shows highly fractured features, where the fractures are interconnected, and therefore, groundwater flows were represented as a continuum. The medium depth zone shows less fractured, but considerably interconnected fractures. The groundwater flow in this regime shows a discrete flow pattern. The lower depth zone shows the least fractured medium, in which case, groundwater flow is inhibited, and the zone acted as an aquitard. This transitional fractured bedrock characteristic may reflect that of the current study area investigated in this thesis.

The study was conducted at the Sycamore Farm Experimental Watershed, in southwestern Ohio. The site is consisted of flat, Silurian, carbonate bedrock overlain by glacial till. The carbonate Dolomite and Limestone are highly fractured in the upper surface region of the bedrock, fracturing decreases with depth. The analysis of flows were carried out with either a continuum approach for a highly persistent and interconnected fractured zone, or a non-continuum approach for a poorly connected, discretely fractured zone. The authors use both field and modeling
methodology to conduct the analysis. Field instrumentations were used to obtain parameters such as hydraulic conductivity and flow fluxes. The borehole flowmeter and pumping tests were used to produce a profile for hydraulic conductivity, where the hydraulic conductivity can be calculated from the following equation:

\[ K_i = K_p \frac{(\Delta Q_i)/(\Delta Z_i)}{(Q_p)/B} \]

where \( K_p \) is the hydraulic conductivity determined from the pumping test, 

\( \Delta Q_i \) is the flux changes over an interval \( i \),

\( \Delta Z_i \) is the thickness of measurement interval \( i \),

\( Q_p \) is the pump discharge,

and \( B \) is the aquifer thickness.

The results show a large contrast in hydraulic conductivity within the disconnected fractures zone, while hydraulic conductivity in the upper interconnected fractures zone remains largely uniform. The hydraulic conductivity of the lower zone shows very low values, typical of an aquitard. The authors note that the fluid injection technique may be more suitable for investigating single fractures than the pumping technique. A three-dimensional finite difference flow modeling was conducted for the test site using multiple layers to delineate the different zones. The results show very complex capture zone geometry. The study shows that the largest capture zone extent persisted in the discretely fractured zone. Multiple isolated areas may also form.
4.0 Methods
To delineate the groundwater capture zone boundary for the study area, a numerical model was constructed using the USGS based software, Visual MODFLOW. The parameters inputted were estimated as outlined in the following sections. Boundary conditions were also outlined based on geographic and geologic information. Elevation data were manually obtained from the YGS MapMaker Online, compiled into an excel spreadsheet and then imported into the MODFLOW software. An aerial extent of 16.6 km by 19.4 km centered at latitude 62° 15’ 30” and longitude 133° 14’ 38” was modeled, and covers the whole of the Grum pit watershed, and adjacent watersheds.

4.1 Parameters Estimation

4.2.1 Soil Properties
Necessary soil properties that need to be acquired are porosity and effective porosity values. The Grum pit is located in an area with variable soils ranging from silty till to sands and gravels. From previous reports, these materials show ranging porosity values from 0.25 to 0.50 with effective porosity values ranging from approximately 0.15 to 0.35 (Environmental Science Division, U.S. Department of Energy). For the purpose of this study, an intermediate value for porosity and effective porosity was selected to be 0.30 and 0.15 respectively, and are deemed representative for the general material properties in this area.

4.2.2 Hydraulic Conductivity
A series of groundwater monitoring wells were drilled in the Faro Mine Complex area to obtain groundwater parameters and information. One monitoring well was drilled and installed in the Grum rock dump area. The hydraulic conductivity values obtained was determined from a series of rising and falling head slug tests, where the obtained data was
analyzed using the Hvorslev analysis and for cases of data fluctuations, the van der Kamp model. The hydraulic conductivity for the Grum pit area was determined to be ranging from $8 \times 10^{-6}$ m/s and $2 \times 10^{-5}$ m/s as mentioned in the above section. Due to the presence of silts and fine materials, the lower limit of $8 \times 10^{-6}$ m/s was selected for the base case model. This lower boundary value of hydraulic conductivity was also selected to account for the undulating presence of the fractured phyllite bedrock. The phyllite bedrock hydraulic conductivity was determined to be approximately $1 \times 10^{-8}$ m/s. In the case where the phyllite bedrock is fractured, the hydraulic conductivity will most likely be higher than the anticipated value of $1 \times 10^{-8}$ m/s.

4.2.3 Recharge Rate

The recharge rate was obtained from a water balance report for the Grum area. Water balance data was gathered from meteorological stations, snow surveys, seepage weirs, and infiltration studies. The annual groundwater recharge rate for the Grum pit area was calculated over a 1.60 km$^2$ area using the following equation:

$$R_e = S + R - E - R_s - R_f$$

where $R_e$ is the soil and groundwater recharge (mm),

$S$ is the snowmelt (mm),

$R$ is the rainfall (mm),

$E$ is evaporation (mm),

$R_s$ is snowmelt runoff (mm),

and $R_f$ is rainfall runoff (mm).
The analysis, conducted for year 2004/2005 shows a mean annual recharge value for the Grum area to be 229 mm/year. Comparing with historical data gathered at the Faro Airport, mean annual precipitation in the area ranges from 171 mm/year to 420 mm/year. The mean annual recharge of 229 mm/year thus appears to be an appropriate approximation. However, in the dry period, the recharge rate for the Grum waste rock dump area is expected to be lower.

4.2 Groundwater and Boundary Conditions
The study area is situated in a remote area. Thus, due to limited monitoring information, no information regarding groundwater level and water stages of the existing creeks were found. The analysis was thus conducted assuming the water stages for the streams to be hydrostatic with topographic elevation. A geographic map with elevation contours was generated on YGS MapMaker Online. Based on the elevation contour, and observing the streams drainage pattern, a topographic groundwater divide was located approximately 2.8 km west of the Grum pit, where the creek west of Grum pit drained the west side of the small mountain range to the west of the pit. A second topographic divide was located approximately 3 km east of Grum pit, where the Vangorda creek drained the west side of the mountain range observed in this area. The upper boundary was set at approximately 10 km northeast of the pit, where the peaks of the mountain range that dominate this area are located. The lower boundary was delineated by the lower Vangorda creek, which runs westward towards Faro town.

4.3 Model Grid and Set Up
The numerical model covers an area of 322 km², centered at latitude 62° 15’ 30” and longitude 133° 14’ 38”. The model has a grid spacing of approximately 185 m. Inactive cells were assigned to encompass the groundwater divide boundaries identified above. The eastern boundary was extended to incorporate into the model the Vangorda pit lake, which will also be
acting as a hydraulic sink. This is so that the effects of the Vangorda pit on the Grum pit’s capture zone can also be investigated in the study. The western boundary was extended beyond the groundwater divide to encompass the adjacent watershed, as the divide boundary lies too close to the Grum pit area to be confident that the no-through boundary between the two zones remains a solid boundary. The model grids were refined around both the Grum and Vangorda pit lakes to allow for a more refined modeling of the pit area elevations and constant heads. The grid spacing in these areas are approximately 40 m. Elevations data were compiled from the YGS Online MapMaker together with the Grum and Vangorda site maps obtained from previous reports conducted by SRK Consulting and was incorporated into the model. Figure 4 below illustrates the final model grids and elevations.
The creeks were incorporated into the model as constant heads hydrostatic to topographic elevations. The two pit lakes were also assigned as constant heads, where the latest stage data was obtained from 2003. Figure 5 below illustrates the active and inactive zones outlined, and the boundary conditions of the numerical model.
The model was divided into 5 layers, with layer 1 set to be approximately 450 m thick, layer 2 to 4 set to be approximately 150 m thick, and layer 5 approximately 100 m thick. The assigned constant heads values and recharge rate apply only to the top layer. A cross sectional view is illustrated in Figure 6 below across column 70, which passes over the Grum pit.
5.0 Model Cases and Results

To achieve a most representative model of the actual site conditions, the numerical model was calibrated through simulations of various cases. The model was thus divided into five different cases to explore various conductivity conditions, where sensitivity analyses were also conducted for various recharge values and various hydraulic conductivity values for the topmost layer.

5.1 Case 1: Homogeneous K System

In the first case modeled, a homogeneous system was assumed where there are no variations in the hydraulic conductivity of the active zone with depth. The active zone in the model was assumed to be composed of colluvial sands and gravels, and tills as identified in previous geotechnical reports. The hydraulic conductivity of the material ranges from $8 \times 10^{-6}$ m/s to $2 \times 10^{-5}$ m/s. To better represent the presence of underlying bedrock, the lower boundary of $8 \times 10^{-6}$ m/s was chosen for this first case. Table 1 below summarizes the input parameters into the MODFLOW software.

<table>
<thead>
<tr>
<th>Table 1. Model input parameters for Case 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Porosity</td>
</tr>
<tr>
<td>Hydraulic Conductivity (Layer 1 to 5)</td>
</tr>
<tr>
<td>Recharge</td>
</tr>
<tr>
<td>Grum Pit Constant Head Level</td>
</tr>
<tr>
<td>Vangorda Pit Constant Head Level</td>
</tr>
</tbody>
</table>

The model was run using the Waterloo Hydrogeologic Solver (WHS), where the maximum iteration number had to be reset to 200 iterations for the model to converge. Particle tracking was used to illustrate flow path patterns. Random arrays of particles were laid down across the active
zone, with a higher concentration around the pit area. The flow paths outlined by the particle tracking option of the MODPATH module delineate the capture zone of the Grum pit illustrated in Figure 7 below.

Figure 7. Case 1 capture zone boundary.

The analysis result shows that the Grum pit capture zone is not influenced by the presence of the Vangorda pit, which implies that the Grum pit act independently of the Vangorda pit. The Grum watershed area, disregarding the Vangorda pit, thus encompasses an area of approximately 18 km². The capture zone outlined in this case encompasses an area of approximately 12.5 km². The
three dimensional extent of the capture zone is presented in the cross sectional view of the particle paths illustrated in Figure 8 below.

Figure 8. Cross sectional view illustrating Case 1 capture zone extent.

Assuming a wholly homogeneous system of the study area, the capture zone extends up to a depth of 800 m from the leveled area elevation of 1300 m. The cross sectional view shows that a deeper regional groundwater flow would likely bypass the pit, and travels across to the nearby creek. However, assuming that the study area is wholly homogeneous would be incorrect due to the large difference in hydraulic conductivity values between the overburdens and the underlying phyllite bedrock. The presence of phyllite bedrock was then incorporated into case 2 as discussed in the following section.

5.2 Case 2: Homogeneous K Bedrock

To incorporate the phyllite bedrock into the model, a different hydraulic conductivity value was assigned for the lower layers of the model. Without changing the other model input parameters previously inputted in Case 1 above, the bedrock hydraulic conductivity value of $1 \times 10^{-8}$ m/s was applied to layer 2 to 5. The cross sectional view presenting the hydraulic conductivity distribution amongst the five layers is presented in Figure 9 below.
Figure 9. Hydraulic conductivity spatial distribution from layer 1 to 5.

Using the same particle array, with larger concentration around the pit area, the result generated is as shown in Figure 10 below.

Figure 10. Case 2 capture zone boundary.
By assigning a different hydraulic conductivity values from layer 2 to 5, thus incorporating the phyllite bedrock into the model, the capture zone boundary is changed. The northern boundary is reduced by approximately 1 km, while the southern boundary extends by approximately 500 m. The new capture zone delineated in this case encompasses an area of approximately 14.5 km$^2$. To investigate the three dimensional extent of the capture zone, a cross sectional view across the pit was taken and is illustrated in Figure 11 below.

![Figure 11. Cross sectional view illustrating Case 2 capture zone extent.](image)

The capture zone also extends in depth as the bedrock is incorporated into the model, and now encompasses the whole depth of the model. No deeper flows were observed to be bypassing the pit. By acknowledging the presence of the phyllite bedrock, the capture zone boundary encompasses a larger area, which suggests that, as flows are most likely limited within the topmost layer, where a higher conductivity value is present in the topmost layer, more preferential flows are directed towards this layer. However, the model layout in Case 2 does not take into considerations surface erosion effects. As discussed in Podgorney & Ritzi’s article on “Capture Zone Geometry in a Fractured Carbonate Aquifer”, surface erosion could cause a variation in fractured bedrock conductivity. From previous geotechnical report, the phyllite bedrock in the Grum pit area also appears to be fractured near the surface. The effects of surface erosion on the bedrock layers are investigated in Case 3 below.
5.3 Case 3: Surface Erosion Effects on Bedrock

To take into consideration the effects of surface erosion on the phyllite bedrock, the top layer of the bedrock zone, represented by layer 2 of the model, is assigned a higher hydraulic conductivity value. Table 2 below summarizes the hydraulic conductivity values assigned to the respective model layers.

Table 2. Hydraulic conductivity values assigned.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>$8 \times 10^{-6}$ m/s</td>
</tr>
<tr>
<td>Layer 2</td>
<td>$1 \times 10^{-7}$ m/s</td>
</tr>
<tr>
<td>Layer 3 to 5</td>
<td>$1 \times 10^{-8}$ m/s</td>
</tr>
</tbody>
</table>

The spatial distribution of the hydraulic conductivity value is illustrated in cross sectional view in Figure 12 below.

![Figure 12. Hydraulic conductivity spacial distribution from layer 1 to 5.](image)

Using the WHS solver, with the same particle arrays as the previous two cases, the flow path delineating the Grum pit capture zone is shown in Figure 13 below.
Figure 13. Case 3 capture zone boundary.

By applying a higher hydraulic conductivity value to layer 2, the capture zone boundary diminishes slightly on the southern boundary, where the southern limit shortened by a length of approximately 200 m. The capture zone now covers an area of approximately 14 km². The three dimensional extent of the capture zone is illustrated through a cross sectional view taken across the pit in Figure 14 below.
Figure 14. Cross sectional view illustrating Case 3 capture zone extent.

The capture zone appears to extend to a deeper depth by applying a higher hydraulic conductivity value to layer 2, the topmost layer of the bedrock zone. The capture zone boundary extends in depth as flows are more willing to flow across the higher conductivity zone within the bedrock. This model setup is then used as the most representative model set up for the study area concerned.

5.4 Case 4: Varying Hydraulic Conductivity Sensitivity Analysis

Case 3 discussed above depicts a most representative condition of the actual study area field condition. Thus, it would appear that the capture zone geometry is by large governed by the hydraulic conductivity. To test this presumption, using the same baseline model set up in Case 3, the hydraulic conductivity of the topmost layer is varied to observe the changes this would pose on the capture zone. The hydraulic conductivity of the top layer was first decreased by a factor of 8, from $8 \times 10^{-6}$ m/s to $1 \times 10^{-6}$ m/s. The result is illustrated in Figure 15 below.
Figure 15. Capture zone boundary for $K = 1 \times 10^{-6}$ m/s in Layer 1.

Decreasing the hydraulic conductivity of the top layer by a factor of 8 does not seem to affect the capture zone geometry as much in aerial extent. However, when observing the three-dimensional flow pattern by exploring the cross sectional view, it can be observed that the flow pattern in the subsurface is changed. This is illustrated in Figure 16 below.
Figure 16. Cross sectional view for $K = 1 \times 10^{-6}$ m/s in Layer 1.

As there are less contrast in the hydraulic conductivity values between the top layer and the subsequent layers, there is less driving force for the groundwater to preferentially flow into the top layer. This explains the more gentle flow pattern observed in this case.

To further investigate the effects of hydraulic conductivity on the capture zone geometry, a higher hydraulic conductivity condition was analyzed. The hydraulic conductivity of the topmost layer is then increased by an order of magnitude, from $8 \times 10^{-6}$ m/s to $1 \times 10^{-5}$ m/s. The result is illustrated in Figure 17 below.
By increasing the hydraulic conductivity in this case, the capture zone aerial extent is reduced slightly in the southern part of the pit. This may be due to enhanced topographic effects facilitated by the increase in hydraulic conductivity. The three-dimensional flow pattern was also observed for changes as illustrated in Figure 18 below.
By increasing the hydraulic conductivity, there is a greater contrast in hydraulic conductivity values between the top layer and the subsequent layer, thus promoting a preferential flow towards the top layer. Thus, it is observed that the capture zone extends to a greater depth when the hydraulic conductivity of the topmost layer is increased.

5.5 Case 5: Recharge Rate Sensitivity Analysis
The governing factor for the capture zone geometry of the study area appears to be that of hydraulic conductivity distribution. To test this hypothesis, sensitivity analysis was conducted for one other varying factor that could potentially influence the capture zone, the annual recharge rate, using the model setup of Case 3 above. Figure 19 and 20 below illustrates capture zone extent for recharge values representing 50% of the originally assigned recharge rate for the study area of 229 mm/year.
By reducing the recharge rate to 50%, the capture zone aerial extent reduces slightly with the shrinkage of the southern boundary. At depths, gentler flow patterns were observed, where the capture zone boundary at depth seems to extend to a greater depth. A recharge rate at 10% of the
original recharge rate was also modeled and analyzed. Figure 21 and 22 below illustrates the capture zone extent for such a case.

Figure 21. Capture zone boundary for a 10% recharge rate.

Figure 22. Cross sectional view illustrating capture zone extent for a 10% recharge rate.

By changing the recharge rate from 50% to 10% of the original annual recharge rate, the aerial extent of the capture zone does not show any changes in geometry. However, at depth, by
reducing the recharge rate, the capture zone seems to extend to a greater depth. This may be due to the fact that as there are less flow across the system, there is less driving force for the groundwater to flow across the system, and thus, a gentler flow pattern can be observed, where the groundwater are not pressured to flow through the system and recharges into the pit.

6.0 Discussions and Conclusions
From the numerical model analyses conducted, the model scenario that would most accurately represents the actual field condition of the Grum pit area and its groundwater flow system would be that of Case 3 discussed in section 5.3 above. Case 3 scenario depicts a system with decreasing hydraulic conductivity with depth. The top layer represents the sands, gravels and silts layer, which has been identified to be a common material type from previous geotechnical report of the Grum and Vangorda area. Due to previous borehole logs showing undulating bedrock locations, where the phyllite bedrock is discovered at depths of approximately 20 m and 40 m in some area, and undiscoverable in others, the lower bound hydraulic conductivity was adopted to account for the inconsistent presence of the bedrock within this layer. The second layer depicts a phyllite bedrock layer, which has been weathered due to surface erosion, and thus, a higher hydraulic conductivity value was adopted. However, due to the limitation of the software’s capability, the effects of interconnected fracturing or discrete fracturing could not be thoroughly explored. The remaining layers of the model were assigned a lower hydraulic conductivity value to depict that of intact bedrock, which essentially serves as an impermeable layer. Due to the lack of past investigation data, isotropic conditions were assumed for the whole watershed concerned in the study area. This may cause some uncertainties and inaccuracies in the model as the actual field conditions may not be simply represented by an isotropic condition. Subsurface irregularities in material properties may affect the modeled results. As the study area
is located in a remote area, where official information on streams data is not obtainable, constant heads hydrostatic to topography were manually assigned to the creeks and streams contained in the study area, which pose as another source of uncertainty in the modeled results.

However, for a preliminary study, the simulated model is sufficient in delineating the approximate geometry of the Grum pit’s capture zone. The model also allows for the investigation of various governing parameters and conditions that may influence the geometry of the capture zone. From the analyses conducted, the capture zone of the Grum pit area covers an aerial extent of approximately 14 km², which captures all flows throughout the depths of the study area. However, the capture zone does not cover the whole extent of the waste rock dump, as some flows in the southern portion of the dump would lie beyond the extent of the capture zone, and will terminate its flow at the southern Vangorda creek.

The groundwater flow direction in this case is governed wholly by the topography of the area. However, the capture zone geometry is largely affected by the hydraulic conductivity distribution. By changing the hydraulic conductivity distribution of the subsurface layers, the capture zone geometry is significantly changed, moving from a homogeneous condition to a heterogeneous condition at depths. By depicting a bedrock layer with low hydraulic conductivity condition in the lower layers, the capture zone increases in aerial extent. From the sensitivity analysis conducted, it was also observed that the different contrasts in hydraulic conductivity values of the topmost layer and the subsequent layers also influence the flow patterns of groundwater in the subsurface. When a higher contrast of values were observed, the capture zone appears to extend towards greater depths as preferential flows towards the top layer with higher conductivity values are promoted. However, the presumption that the capture zone geometry is governed only by the hydraulic conductivity does not pertain. By conducting a sensitivity
analysis of different recharge rates, it appears that although the aerial extent of the capture zone does not change significantly, the geometry of the capture zone at depths is largely affected. By decreasing the recharge rate, the flow pattern changes from a rapid surge towards the pit to a more gentle movement towards the pit. This may be due to the reduction in flow driving force due to less infiltration.

7.0 Recommendations for Further Work
There are many limitations to the applicability of the model conducted at this stage towards actual field conditions due to a lack of existing data pertaining to detailed geotechnical and hydrogeological information. Identifying the actual extent of the capture zone for this pit area may be important for future works, especially in site remediation where concerns about acid rock drainage is crucial. To improve modeling works, more piezometers and observation wells may be of benefit in obtaining current groundwater information. Stream gauging may also help improve the quality of modeling tasks. Core loggings may also be conducted to obtain geotechnical information that would be current to the existing state of the pit area after various mining tasks have occurred in the area since the last investigation conducted.
8.0 List of References


Appendix I

Faro Mine Complex: Vangorda and Grum Area Map
Appendix II

- Boreholes Location Map
- Borehole Logs
- W-E Cross Section, 2003
- W-N Cross Section, 2003
- SW-NE Cross Section, 1996
SRK-03-TP3

Easting  592479  NAD27  Northing  6903017

0-2.0 m:  Gravelly SAND, trace silt
          Olive grey, occasional pods of fines (<5%), occasional oxidized gravel
          particles.

2.0-4.6 m:  SAND, minor silt (5%)
            Trace gravel. Sand and gravel are angular flat particles of weathered dark
            grey to black phyllites, commonly open framework, with occasional layers
            of silt infill. Unit bears water at ~3 m; volume sufficient to fill bottom of
            pit prior to backfill. No permafrost encountered.

4.6 m:  EOH

Water at 3 m.

Photos: 100-0420 to 100-0426

SRK-03-TP4

Easting  592359  NAD27  Northing  6902968

0-1.0 m:  Till, sandy SILT
          Olive brown, low plasticity, fissile, trace gravel.

1.0-3.0 m:  Bedrock, black shale
            Fold structures visible in pit wall. Rock type not phyllite. RQD=0. No
            water or permafrost encountered.

3.0 m:  EOH

Photos: 100-0427 to 100-0429
September 17, 2003
Geotechnical Investigation
Proposed Grum Seepage Collection Ditches

4 test pits excavated north of Grum toe access road west of V15, using the Caterpillar 235 excavator from site operated by site staff (John). Supervision of excavation was done by Dylan MacGregor.

**SRK-03-TP1**

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0-0.05 m: White volcanic ash

0.05-1.0 m: Sandy GRAVEL
Rusty, little to no fines

1.0-3.5 m: Till, sandy SILT
Olive green to olive brown, 5% gravel, low plasticity, no water inflow, no permafrost observed

3.5 m: EOH

Photos: 100-0403 to 100-0407

**SRK-03-TP2**

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0-3.9 m: Till, sandy SILT with 10-15% gravel
Olive brown, moist, occasional oxidized gravel particles. Test pit in center of old road; road cut showed 0.8 m of similar material. No water inflow observed, no permafrost encountered.

3.9 m: EOH

Photos: 100-0408 to 100-0412
Profile along centerline of Seepage Collection Ditch (metres)