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

by

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Abstract

The purpose of delineating the capture zone of the Faro Mine is to predict groundwater flow in the area for predicting the Mine's natural potential for capturing contaminated water from the Faro Mine's waste rock pile. The groundwater flow of the Faro Mine was modelled using Visual MODFLOW to delineate the capture zone of the Faro Mine, ultimately the location of the main pit and the Zone 2 pit.

Boundary conditions, parameters and background information were obtained from literature research and extracted from technical reports. As a result, a numerical model was constructed from incorporating the obtained data. Five cases were constructed for conducting sensitivity analysis, with Case 1 being the base case.

Analysis concluded that the most sensitive parameter was the change in water level of the Faro Mine main pit and the Zone 2 pit. Further sensitivity analysis concluded that parameter estimates were not sensitive, which contributed to very little change in the capture zone pattern.

It is concluded that the capture zone geometry at the Faro Mine only encompass 50% or less of the waste rock dump area. Therefore the capture zone has a low potential for capturing contaminated water and further treatment is necessary for remediation.

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I would like to thank the following for their contribution to this thesis: Dr. Leslie Smith for his patience throughout the development and completion of this thesis. Dr. Mary Lou Bevier for her assistance of the thesis process.

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1.0 Introduction

The Faro Mine, a closed lead and zinc mine located in the Yukon Territory, Canada, spans an area of over 25km^2. This mine is part of an operation called the Faro Mine Complex that includes three distinct areas: the Faro Mine, the Rose Creek tailings and the Vangorda Plateau. The Faro Mine was opened in 1969 and during the 1970s it was one of the largest lead and zinc mines in Canada and in the world (Robertson GeoConsultants Inc, 1996).

Being the largest mine in the complex, the Faro Mine consists of three open pits (Zone 1, 2 and 3), underground workings, rock dumps, a tailing impoundment and water management structures. In the 1980s, Cyprus Anvil Mining Corporation began operating at the Faro Mine. In 1994, Anvil Range Mining Corporation bought the mine but did not carry out any mining (Robertson GeoConsultants Inc, 1996). Anvil Range Mining Corporation filed for bankruptcy in 1998, and reached a decision to appoint the administration of the mine to an interim receiver. The interim and maintenance costs are currently being paid by the federal government, with approximately $10 million dollars already spent over the last five years (Faro Mine Closure Office, 2009).

Around the main pit, there are around 320 million tonnes of waste rock that were produced from 29 years of operation (Figure 1) (Faro Mine Closure Office, 2009). These waste rock dumps contain sulphide minerals and the crushing that resulted in these waste dumps increased surface area of the sulphur-containing rock, exposing the these rocks in increased surface weathering from exposure to oxygen and water(Faro Mine Closure Office, 2009). Weathering of these waste rock dumps creates acid rock drainage that can disassociate metals into solution from surrounding rocks (Faro Mine Closure Office, 2009). If high levels of metal and acid are produced from this acid rock drainage (Figure 2), it can affect ground and surface water, affecting the community and aquatic life (Faro Mine Closure Office, 2009). The purpose of this thesis is to track the groundwater flow pattern in the vicinity of the main pit at the Faro Mine.

Figure 1. Faro Mine main pit with surrounding waste rock dumps. Provided by Leslie Smith (2006)

From mapping out the groundwater flow pattern in this area, a capture zone can be constructed for the pit and can help predict the flow of the acid mine drainage from these waste rock dumps. A capture zone is the area of the groundwater flow that will be affected by the depression of the pit and captures the groundwater in the pit instead of flowing downstream. Finding the area of the capture zone is beneficial for remediation planning because it can potentially lower remediation costs of treating contaminated water generated by acid rock drainage and the need to intercept waste rock seepage that does not get captured by the pit.

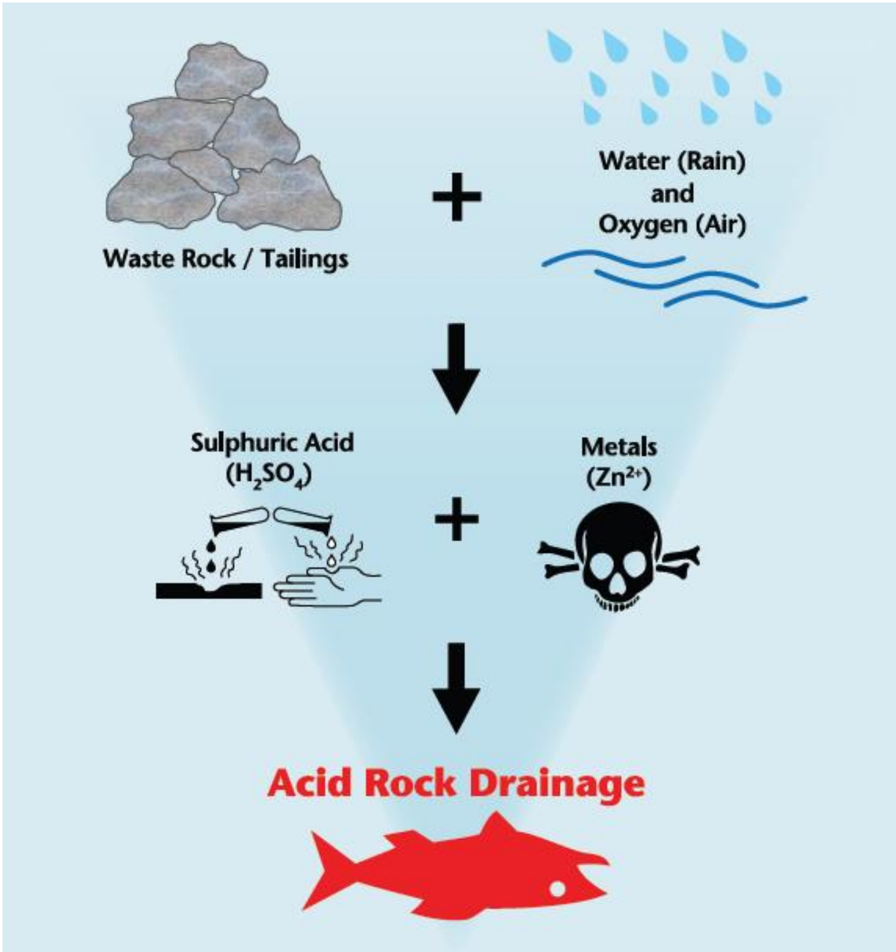

Figure 2 Chemical reactions that form Acid Rock Drainage. Modified from Faro Mine Closure Office (2009)

2.0 Faro Mine Area Background

2.1 Location

The Faro Mine is located in south-central Yukon Territory (latitude 62.36N longitude -133.37W found in Goodfellow and Lydon, 2007), 15km north of the town of Faro. The topography in the study area is dictated by the Yukon Plateau and the surrounding Anvil Range Mountains with elevations above 1800m (Bond, 2001). Within the Faro Complex, the Faro Mine is located in the northwest region and is south-west of the Vangorda Plateau separated by a 13km haul road (Figure 3). This mine occupies the indigenous land of the Kaska Nation and is upstream of the Selkirk First Nations (Faro Mine Closure, 2009).

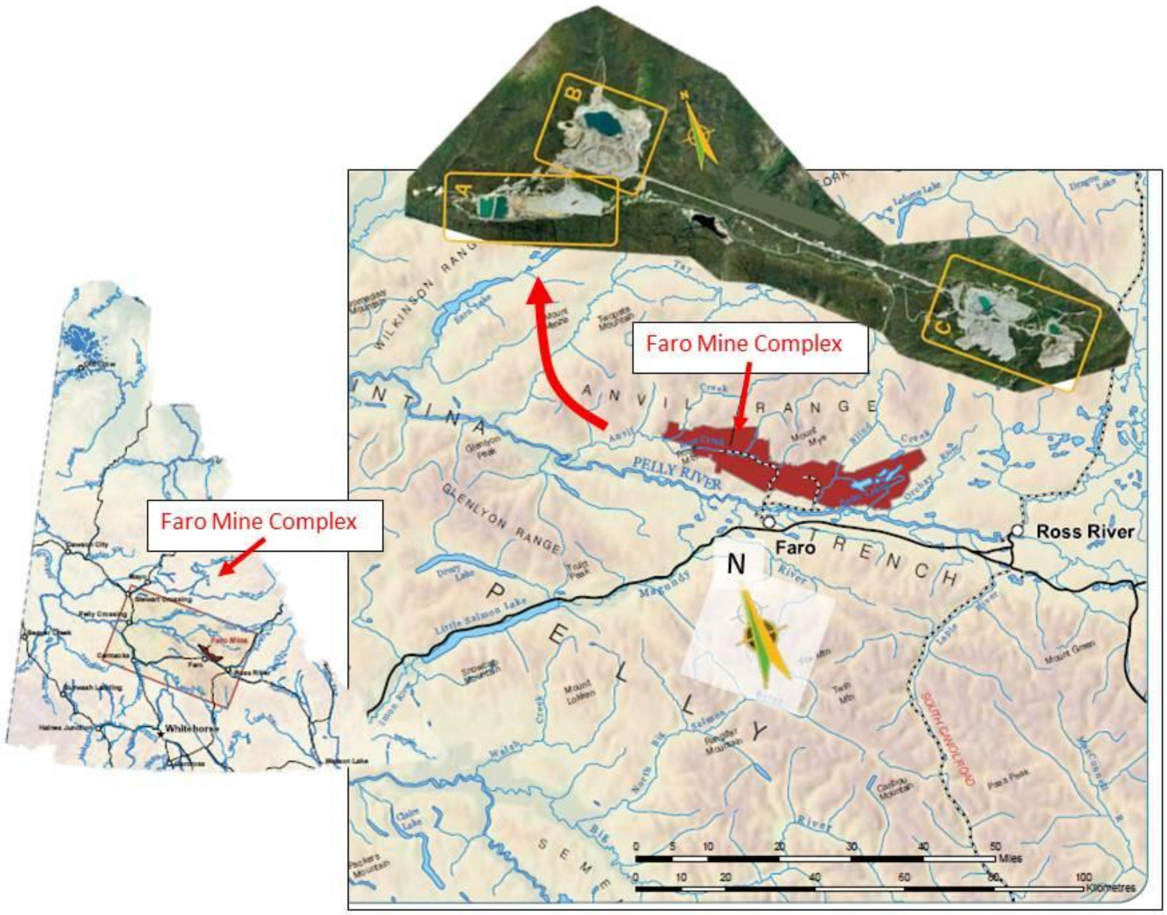

Figure 3. Location Map with site layout at the Faro Mine Complex: A. Rose Creek Tailings B. Faro Mine Area C. Vangorda Plateau. Modified from Faro Mine Closure Office (2009)

2.2 Geological Background

The regional geology of the Faro Mine can be represented by the geology in the Anvil district. Pigage (1999) characterizes this district to be the sedimentary rocks of Precambrian to Jurassic age that makes up the offshelf facies of the Cordilleran miogeocline. A schematic stratigraphy from Pigage(2004) in Figure 5 shows that the three formations in the Anvil district are (from oldest to youngest): Mount Mye, Vangorda and Menzie Creek.

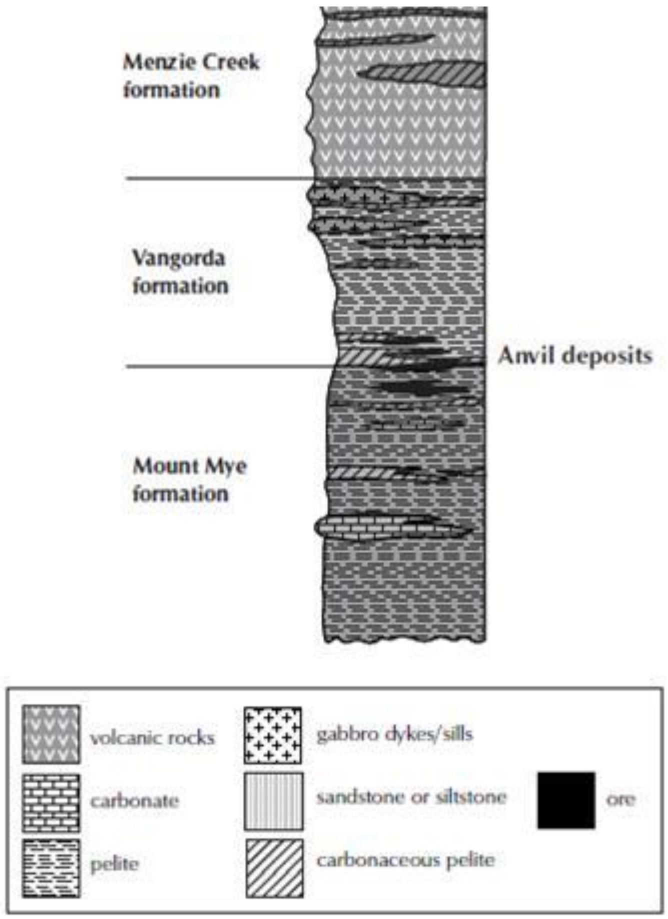

Figure 4. Schematic stratigraphy of the Anvil Deposits at the Faro Mine Complex, Yukon (not to scale). Modified from Pigage (2004)

The Robertson GeoConsultants report from 1996 describes these formations as metamorphosed formations that are in the amphibolite facies and only the Mount Mye and Vangorda formations are visible at the Faro Mine. The Mount Mye formation is further characterized as non-calcareous phyllite and schist with metabasite (Bond,2001) and is represented by schists; while the Vangorda formation is characterized as calcareous phyllite and schist with metabasite (Bond, 2001), and represented by calc-silicates gneiss. The transition between the Mount Mye and the Vangorda formations is gradational (Pigage, 2004). These formations have been regionally metamorphosed and deformed from the nearby Anvil Batholith (Figure 5) beneath the lower contact of the Mount Mye Formation (Pigage, 2004). The report notes that a pronounced horizontal foliation can be seen in the area, resulting in massive sulphide ore-body to be concordant to the formation. The formation along with the ore-body dips slightly to the south-west. Minor faults are found near the ore zone, trending east-west or north-south and a major fault at the south-west end.

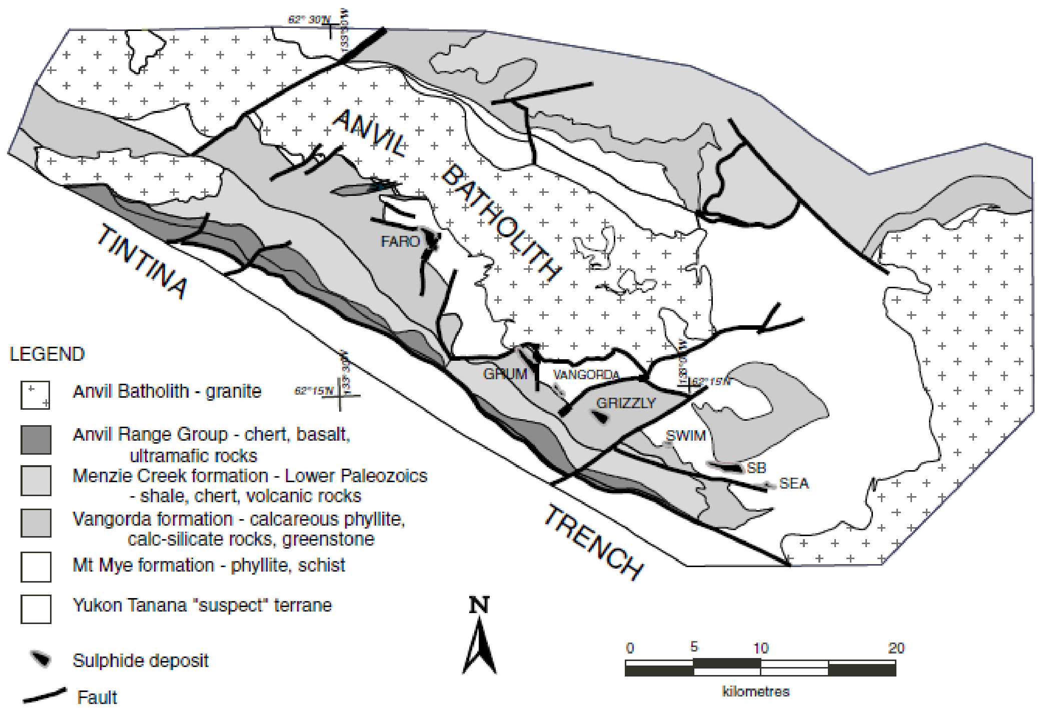

Figure 5. Geology of the Anvil District (Bond, 2001)

Due to the McConnell glaciation, the field area was covered with glacial deposits (Bond, 2001) and the rock units near the Faro Mine are covered with morainal and colluvial deposits with a thickness of up to 100m (Robertson GeoConsultants Inc., 1996).

2.3 Surface Hydrology

Surface water at the Faro Mine is recharged at Mount Aho and Mount Mye which flows through Rose Creek and Vangorda Creek and drains into the Pelly River (Janowicz, 2006). Bodies of water that bound the mine are shown in Figure 6 which includes the main stem of Rose Creek, the North Fork of Rose Creek and Next Creek (Robertson GeoConsultants Inc., 1996).

Initially the pit was established northwest of Faro Creek; however, as mining continued in the early 1970s, the pit was broadened to the south-west and eventually expanded into the southeast, crossing Faro Creek by mid 1970s, leading to the construction of the Faro Creek diversion (Figure 6) (Robertson GeoConsultants Inc., 1996). Presently, the Faro Creek has been diverted to the North Fork of Rose Creek before discharging into Rose Creek, instead of draining to the south into the Faro Creek valley before discharging into Rose Creek. As a result, the total watershed area, the area where all surface water drains into the same body of water, has decreased from 15 km^2 to 2.15 km^2 (Robertson GeoConsultants Inc., 1996).

2.4 Groundwater Hydrology

Groundwater flow paths at the Faro Mine are dictated by the regional geology of the area. Results from the studies done for the 1996(b) Robertson GeoConsultant report show that shallow groundwater flows within the compacted glacial till and is limited by the overburden thinning south-ward toward the valley, although significant groundwater flow can be expected to the north of the pit where there is permeable valley sediments in the Faro Creek Valley. In settings where the glacial till is thick, the groundwater flow will be limited to zones of high-permeability sand and gravel; where the glacial till is thin, the groundwater will flow between the contact of the overburden material and bedrock. Directions of flow paths are found to mimic the surface and bedrock topography. Leakage from the Faro Creek Diversion along the east wall of the main pit is also thought to have the largest contribution to the shallow groundwater.

Robertson GeoConsultants (1996 b) reports that deep groundwater flow is found to be limited in this region, where faults and fractures will account for most of the deep groundwater in bedrock. Fault systems most likely provide a source of deep groundwater flow to the main pit in Faro Mine from the adjacent Zone 2 pit (Figure 8) described in section 2.6.

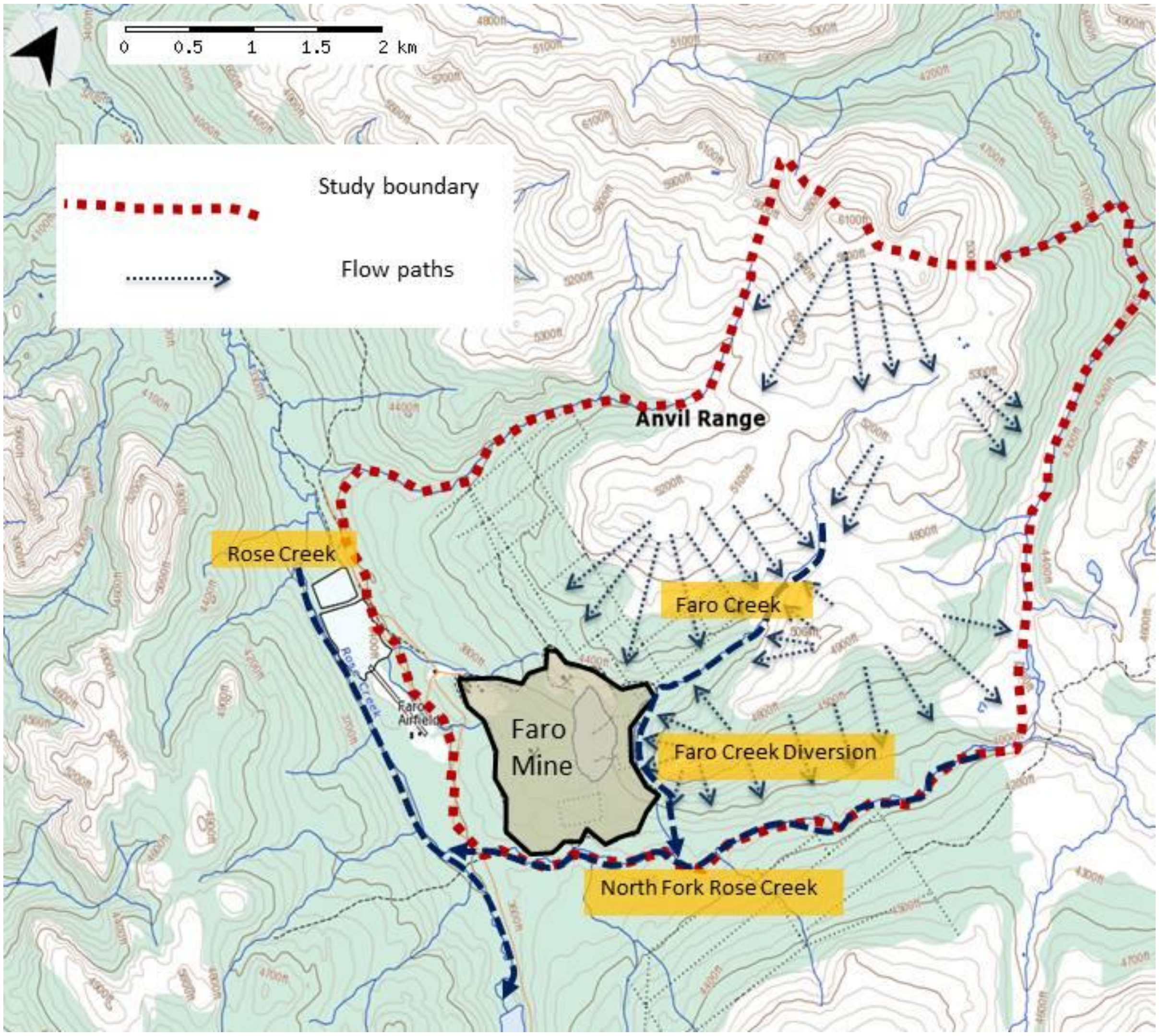

Figure 6. Surface hydrology, groundwater flow directions and model boundary conditions of study area. Modified and Produced from The Atlas of Canada - Toporama – Topographic Maps (2010)

Hydraulic conductivities given from Robertson GeoConsultants (1996 a) are used to determine a hydrostratigraphic model. Bedrock hydraulic conductivities found from packer tests and pump tests indicated numbers from $6x10^{-6}$ m/s to $5x10^{-9}$ m/s. The overburden material that is predominantly silty gravel with sand (Janowicz et al., 2006), was found to average with a hydraulic conductivity of $1x10^{-5}$ m/s, calculated from Darcy's Law using observed piezometric data. Formations at the Faro Mine are extremely deformed and metamorphosed (Pigage, 2004), where one can expect groundwater to flow along foliation as well (Robertson GeoConsultants Inc., 1996 b).

Aquifers at the Faro Mine are limited and the largest aquifer in the study area is the Rose Creek Valley aquifer. This aquifer is in a valley of complex glacial till sediments and underlies the Rose Creek Valley Tailings Facility, but due to the boundaries set for this study (described in Section 3.3), this aquifer is not included.

2.5 Climate

The Faro Mine is in a sub-arctic region of Canada (Janowicz et al., 2006), within the discontinuous permafrost zone (Bond, 2001). This area has a very large annual range in temperature and is subjected to variation from elevation difference. Mean annual air temperature is around -5^{o}C (Janowicz, 2006) with a mean January temperature of -17.7 ^{o}C and a mean July temperature of 14.1 ^{o}C (Government of Yukon, 2010) and can be relatively dry throughout the year. Annual precipitation at Faro is split approximately into half rain and half snow (Government of Yukon) with a measured annual precipitation mean of 316 mm (Janowicz, 2006). The annual evaporation at the Faro Mine site is found to be 141 mm (Janowicz, 2006).

2.6 Zone 2 pit

Faro Mine has two large water reservoirs: the main pit and the Zone 2 pit. Although the main focus of this thesis is on the main pit, the Zone 2 pit also plays an important role in this analysis because of its connectivity to the main pit through fault systems. Robertson GeoConsultants (1996) concluded that at a constant head (water level) of 1110 m above mean sea level (AMSL) in the Zone 2 pit and Faro Mine main pit, seepage will be close to negligible between the two pits due to the formation of a groundwater divide (an equilibrium); and seepage will be mainly controlled by permeability of rocks between the two pits.

In a report written by SRK Consulting (2006), the Zone 2 pit is described as a backfilled pit that was filled with broken rock after excavation. As a backfilled pit, the Zone 2 pit becomes an underground hydraulic sink (reservoir) and a physical pit will not be seen at ground surface. The only indication of the backfilled pit is a standpipe that was installed in the ground for groundwater monitoring and water pumping out of the pit (SRK Consulting, 2006).

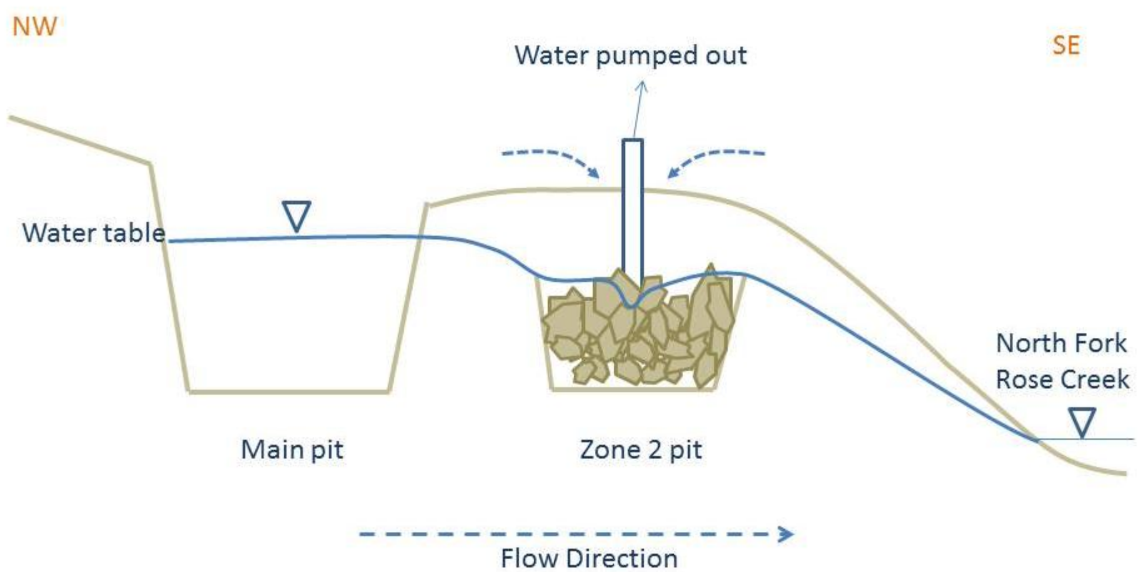

Figure 7. Schematic north-west cross section of main pit, Zone 2 pit and North Fork of Rose Creek, with Zone 2 pit having a lower constant head than its surroundings. Information provided by Leslie Smith (February, 2011))

An important purpose of the pumping well discussed in the SRK Consulting (2006) report is that it will create a cone of depression (an area that is lower in water level than its surroundings and serves to accumulate groundwater) between the main pit and North Fork of Rose Creek (Figure 7). This cone of depression will intercept any contaminated groundwater from the main pit before it reaches North Fork of Rose Creek, contaminating stream water. Since this pit was filled with broken rock, it creates a zone of high porosity zone compared to the surrounding rock.

Currently the Faro Min main pit is maintained at a constant head of 1143 m and Zone 2 pit at 1110 m (SRK Consulting, 2006). As a result of the lower head at Zone 2 pit, contaminated water generated at the Faro Mine will be collected as described above.

Seasonal pumping at this pit serves to discard the captured contaminated groundwater and to maintain a constant head of 1110 m; therefore no overflow of the water will occur at Zone 2 pit towards the North Fork of Rose Creek (SRK Consulting, 2006).

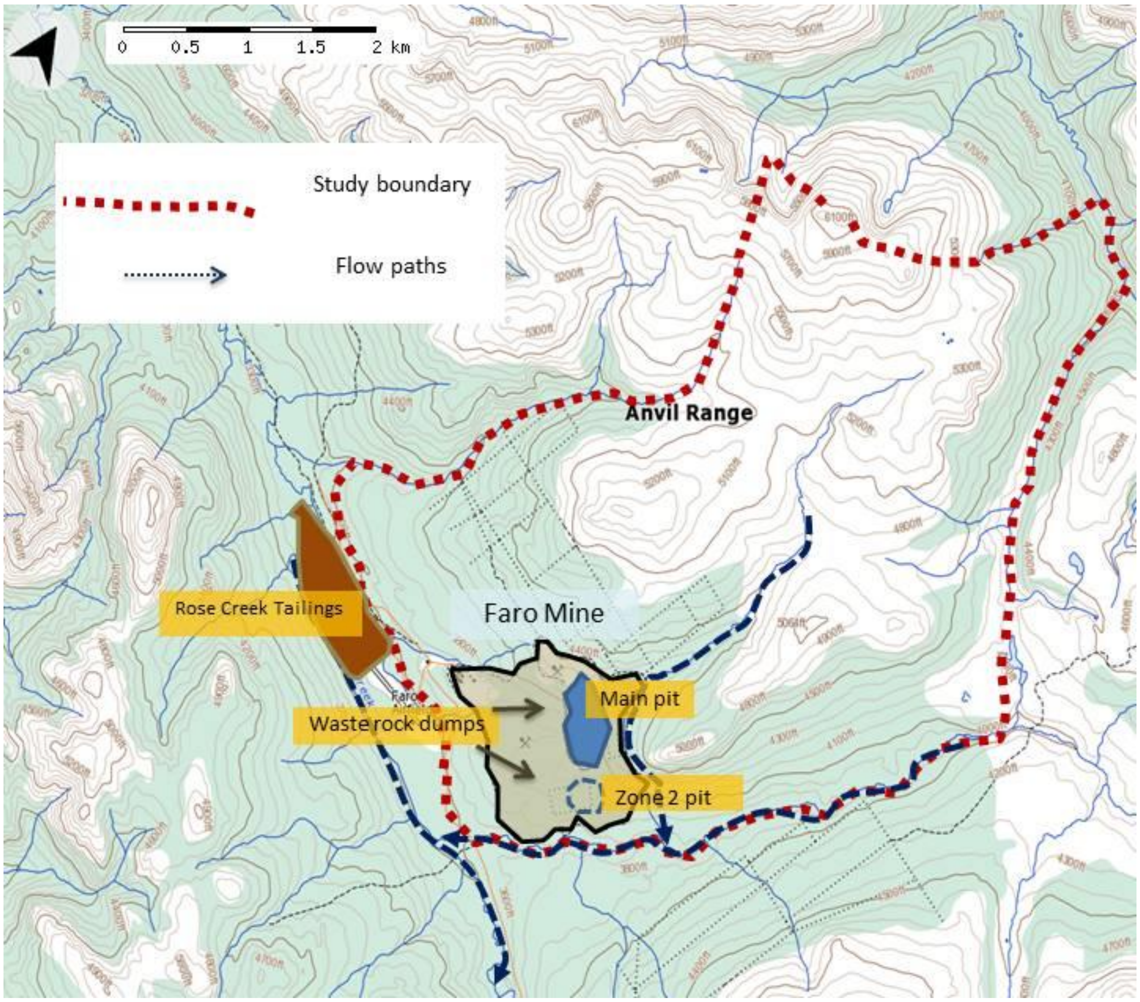

Figure 8. Locations of the Faro Mine main pit, Zone 2 pit, Waste rock dumps and Rose Creek Tailings. Modified and produced from The Atlas of Canada **-** Toporama – Topographic Maps (2010)

2.7 Previous Work

The Faro Mine Closure website (2009) stated that since 1998, Faro Mine has stopped production and is currently undergoing mine closure and remediation plans carried out by the Yukon Government. Numerous investigation reports have been written for this permanent closure, of which includes over 100 technical studies and assessments like seepage investigation to characterize the potential environmental issues at the mine site. Information obtained from these studies was later compiled into several closure options for the mine. Other reports have been written for the mine site in the late 1990's for mine development like drilling and piezometer installations. Geological work was done in the area for mapping purposes and for interest in till geochemistry. No other research similar to this thesis has been conducted in the area before.

3.0 Methodology

3.1 Data source

Due to the nature of this thesis, no field work was conducted. All of the data used for this thesis have been taken from technical reports on the Faro Mine by various consulting companies, mainly the Robertson GeoConsultants report from November 1996. These reports were useful to gain insight on the geological and operating background of the mine. Investigations at this mine were mostly carried out for remediation purposes and only gave limited data that could be used for this thesis. This limitation will permit only a simplified analysis of the groundwater model at the Faro Mine. Published geological literature was used for understanding the geological background of the study area, the nature of the mined deposit, glacial history and geological mineralogy formation.

Map overlays for this model were generated using Toporama from Natural Resources Canada's Atlas of Canada and MapMaker Online from the Yukon Geological Survey. Elevation data was obtained from Natural Resources Canada's GeoGratis National Topographic Database.

3.2 Parameter Estimations

3.2.1 Hydraulic Conductivity

A simple hydrostratigraphic model can be constructed using the hydraulic conductivities stated in section 2.4. Bedrock hydraulic conductivities ranging from $6x10^{-6}$ m/s to $5x10^{-9}$ m/s can be further simplified. Since the dominant rock type in the bedrock is schist and phyllites and have a low calculated transmissivity* value, the non-calcareous schist and phyllite can be assumed as the dominant hydraulic conductivity at $7x10^{-8}$ m/s. This value was obtained from packer tests that were performed on the phyllites at the Faro Mine. Silty gravel and sand overburden material will be assumed to have a hydraulic conductivity of $1x10^{-5}$ m/s.

A low hydraulic conductivity granite batholith underlies a certain part of the model. This layer in the model will be assumed to have a hydraulic conductivity of $1x10^{-10}$ m/s (Argonne National Laboratory, 2011).

**Transmissivity ($T_i = Kh_i*d_i$ (m^2/s)) is calculated by multiplying the hydraulic conductivity (m/s) of a distinctive rock layer by its thickness. A rule of thumb is that if transmissivity number of one layer is 10 times larger than that of the other layer, then the two layers will be considered significant enough to be their own distinctive layer.*

3.2.2 Porosity

Overburden material and bedrock will have to be assigned porosity values for the model. These values include total porosity, defined as the fraction of total void space in the rock (Schlumberger Limited, 2011); and effective porosity, defined as the fraction of pore volume that is only occupied by water adsorbed on clay minerals or other grains (Schlumberger Limited, 2011). Total porosity for silty gravel have a mean of 0.45 and an effective porosity has a mean of 0.20 (Argonne National Laboratory, 2011); and the total porosity for schist bedrock have a mean of 0.05 and an effective porosity has a mean of 0.001. Porosity values are important for this study because these values affect travel time of groundwater through the rocks. The relationship between porosity and travel time is linearly proportional.

3.2.3 Recharge

In an investigation of waste dump water balance completed in 2006 by J.R. Janowicz et al., it was calculated that the annual recharge at the location would be 208 mm, using the Cold Regions Hydrological Model:

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

Where:

R_e = soil and groundwater recharge (mm)	S= snowmelt (mm)	R= rainfall (mm)
E= evaporation (mm)	R_s = snowmelt runoff (mm)	R_r = rainfall runoff (mm)

The recharge of the surrounding land was not found in literature but a reasonable range of 10-20% of the annual precipitation in the area would be used, taking into account of the geology of the ground. The annual recharge rate is thus calculated to be 63 mm. It should be noted that during the period of this study, precipitation measurements were the highest in 26 years.

Hydraulic conductivity	Overburden: $1x10^{-5}$ m/s Meta sedimentary bedrock: $7x10^{-8}$ m/s Granite bedrock: $1x10^{-10}$ m/s
Porosity	Overburden: Total: 0.45 Effective: 0.20 Bedrock Total: 0.05 Effective: 0.001
Recharge	Waste dumps: 208 mm/year Natural ground: 63 mm/year

Table 1. Summary of parameter estimates

3.3 Groundwater and Boundary Conditions

Two recharge conditions are set for the study area because waste dumps at the Faro Mine are more porous, therefore having a larger recharge rate than surround material. The two zones of recharge are shown in Figure 9, where the blue area represents the Faro Mine waste dumps with a recharge rate of 208 mm/year and the white area represents the natural ground with a recharge rate of 63 mm/year.

Boundaries for this study are setup so that constant head (groundwater level) boundaries of rivers and creeks bound the Faro Mine (Figure 10), since groundwater flow will discharge into these areas. The decision to terminate the southern extent of the pit before the Rose Creek Tailings pond is for simplicity in modelling and lack of information regarding the tailings pond.

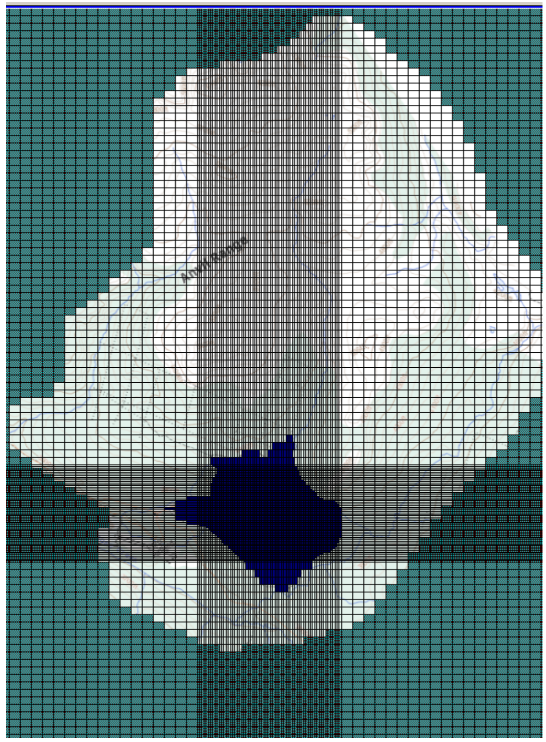

Figure 9. Recharge rate zones of the Faro Mine and its surroundings. Blue area represents the waste dumps area and the white area represents the surrounding natural ground.

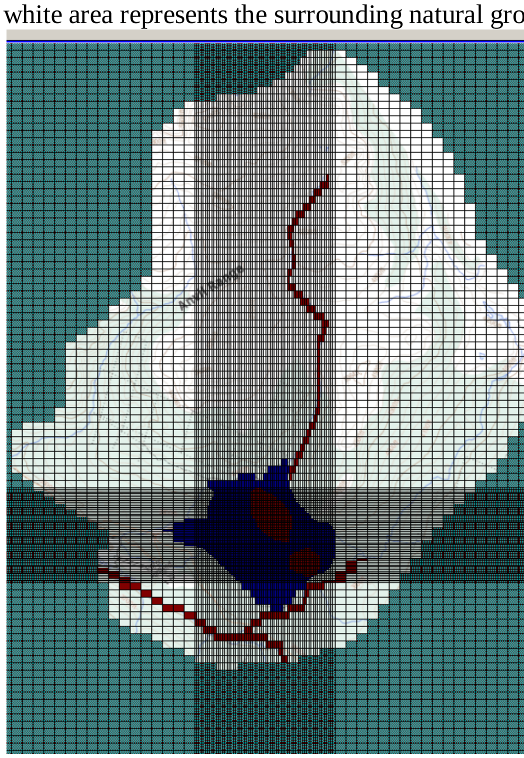

Figure 10. Numerical model boundary conditions. White cells indicate active cells. Red cells indicate constant head boundaries for Faro Creek North Fork of Rose Creek and Rose Creek. Green areas indicate inactive cells.

3.4 Model Grid and Set Up

Visual MODFLOW, a USGS based software for graphical groundwater modelling, was used for this thesis. Parameters were inputted for a numerical model and surficial geographical information like maps and elevation data were imported to Visual MODFLOW to create surface topography (Figure 11). Guiding principles for model setup were taken from Applied Groundwater Modelling (Anderson and Woessner, 1992)

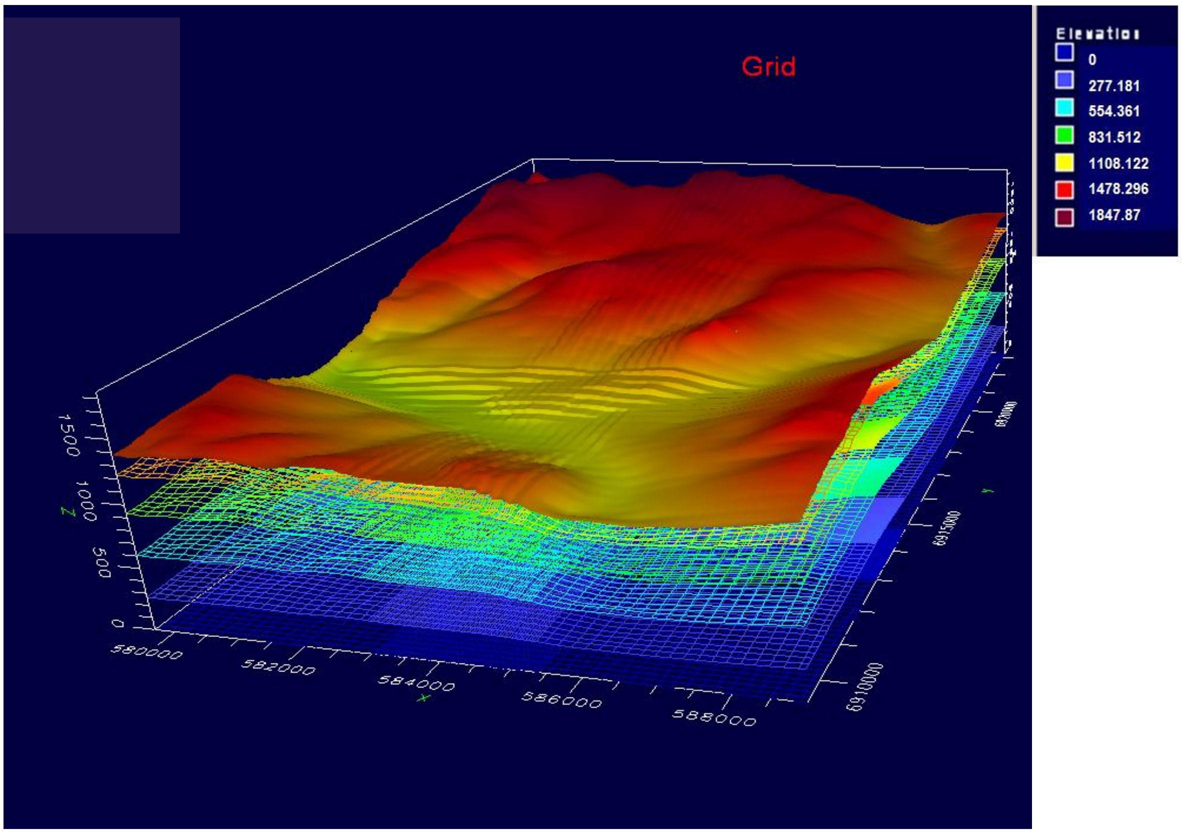

Figure 11. 3D- view of model grid. X- coordinates corresponds to UTM coordinates of the site location, Z- coordinates are corresponds to elevations AMSL in meters.

The active numerical model covers an area of 77 km^2 with grid spacing set to approximately 190 m. Spacing at the vicinity of the Faro Mine main pit and the Zone 2 pit were refined to a spacing of approximately 38 m for a more detailed output. The dimensions of the two pits are described in the following section.

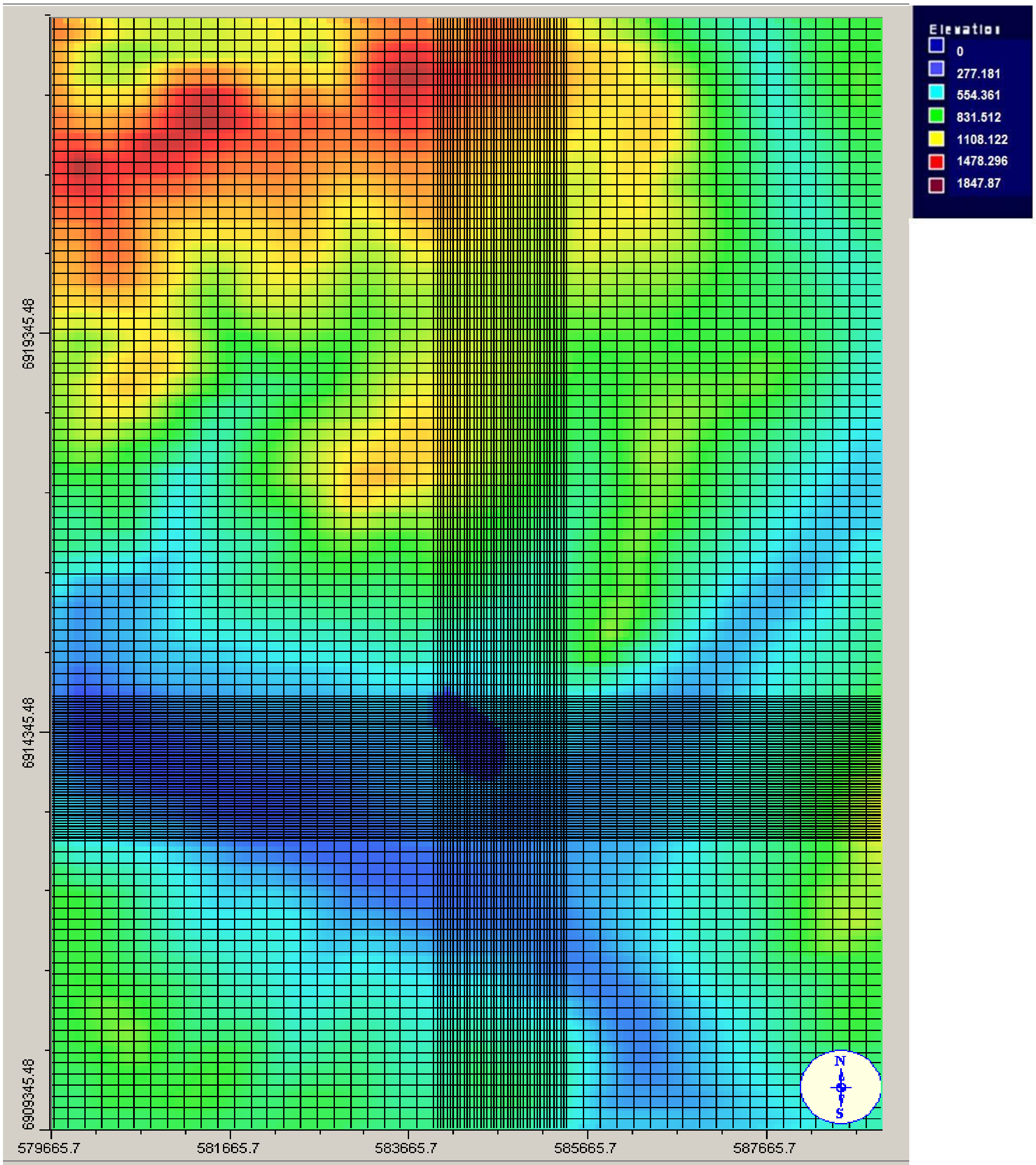

Figure 12. 2D- view of model grid. X- coordinates corresponds to UTM coordinates of the site location, Z-coordinates are corresponds to elevations AMSL in meters.

Inactive cells were used for containing the model within the set boundary condition described previously (Figure 10). The southern boundary of the inactive cells was extended beyond the boundary condition of Rose Creek to allow a more representative flow from the southern part of the Faro Mine.

Constant head boundaries (constant water level) were used for setting up Faro Creek, North Fork of Rose Creek and Rose Creek (Figure 10). Due to the lack of information on the elevation of these surficial water bodies, the creeks were set to surface elevation at their respective locations. Other smaller creeks that do not have names are left out of the model for simplicity. The Faro Creek Diversion was not included into the model because it is a man-made diversion channel and is not a significant creek (Figure 13) like other smaller creeks that were excluded in this model. The diversion creek also has a high seepage into the main pit, and with the exclusion of this creek, it will also provide a better view of water flow into the main pit. The Faro Mine main pit and Zone 2 pit were also to a constant head of 1110 m AMSL.

Figure 13. Faro Creek Diversion- a rock lined ditch that allows Faro Creek to flow around the Faro Mine. Modified from Faro Mine Closure Office (2009).

The model consists of five layers. Layer 1 is representative of the overburden material and is set to a thickness of 100 m. Layer properties that were assigned in Modflow 2000 includes layer 1 as an unconfined layer; layer 2 is assigned to be a confined/unconfined layer; and layer 3-5 assigned to be confined layers. Different hydraulic conductivities are assigned to different coloured layers as shown in Figure 15. Constant heads of the main pit and Zone 2 pit are assigned to layers 1 and 2 because depth of the pits are extended to the layer 2 (Figure 14).

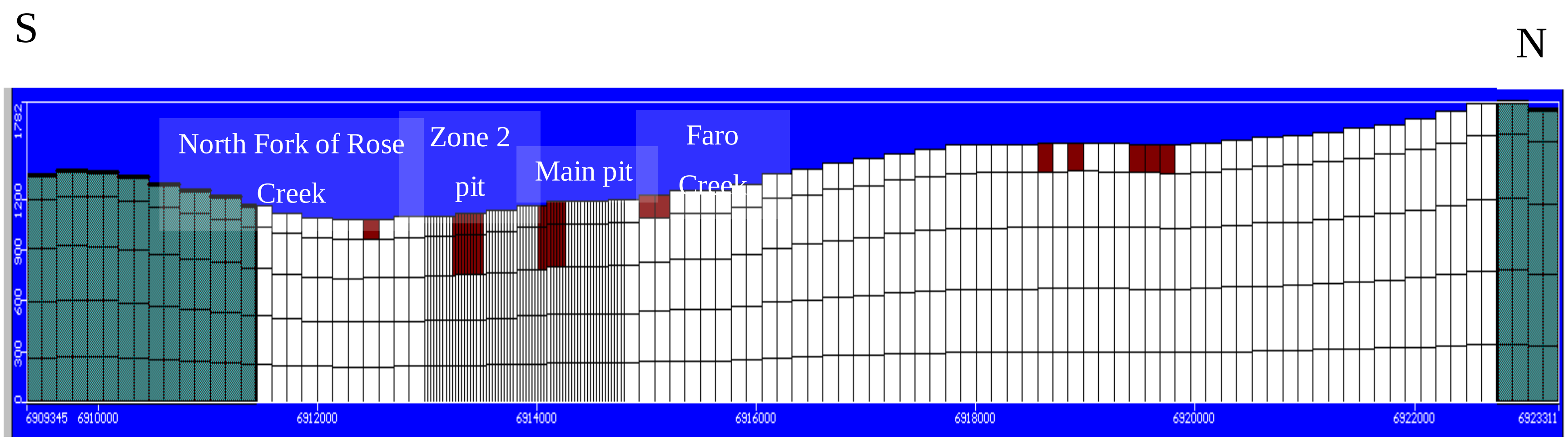

Figure 14. Cross section view of constant head boundaries.

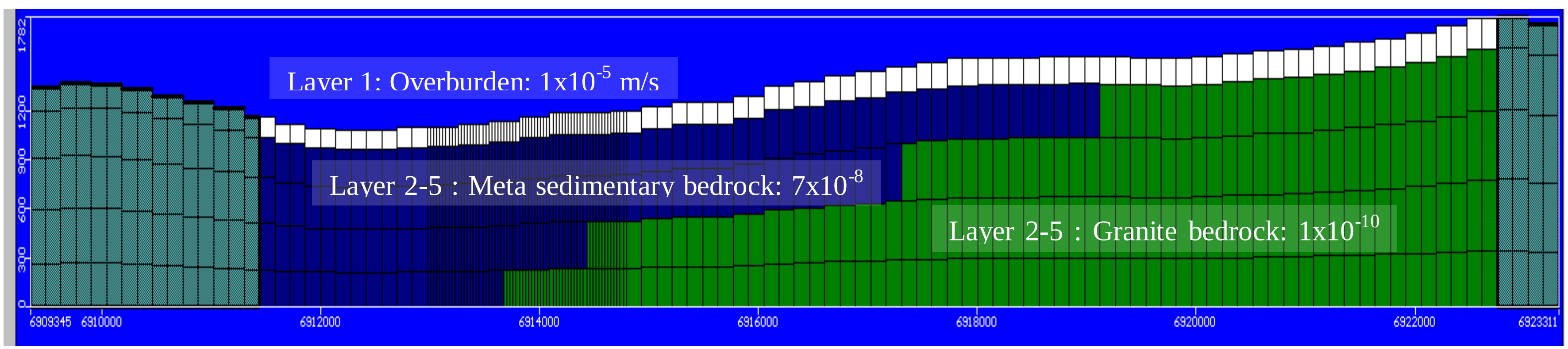

Figure 15. Cross section view of hydraulic conductivity layers.

3.4.1 Pit Geometries

Measurements from the Robertson GeoConsultants report (1996) indicate the following numbers for the Faro Mine main pit and the Zone 2 pit. These numbers have been organized into Table 2 for ease of comparison.

	Faro Mine main pit	Zone 2 pit
Dimensions:	1675m long ; 975m wide	n/a
Circumference:	4.2 km	1.9 km
Surface area:	1.06 km^2	0.24 km^2
Lowest point:	975 m above mean sea level	1094.5 m above mean sea level
Depth:	130.07 m	76.2 m

Table 2. Summary of pit description for Faro Mine main pit and Zone 2 pit.

3.4.2 Case Setup

To create a representative model of the Faro Mine, five cases were created to simulate groundwater flow paths at the site. Tracking particles were incorporated into layer 1 to track groundwater flow paths at the site. Forward particle tracking (which tracks the flow of natural groundwater direction) and backward particle tracking (particles that track back to the source of groundwater flow) were simulated for a better understanding of each case. Setup of the forward tracking particles are shown in Figure 17 and backward tracking particles are shown in Figure 18. Forward tracking particles were set up randomly around Faro Mine to track groundwater flow going into the pit. A more concentrated area of particles was setup in the vicinity of the waste rock dumps as this is the main area of interest for this thesis, because contaminated water is generated in this area. Backward tracking particles were set up at the perimeter of the pits to back-track resulting flow paths of those particles. Sensitivity analysis will be performed for parameters such as hydraulic conductivities of the meta-sedimentary layer, recharge rate and constant head value of the main pit.

Results presented for each case will include forward and backward tracking for a better analysis of groundwater flow and cross-section tracking shown along column 64 of the model (Figure 16) for forward tracking. Column 64 was used because it intersects both the main pit and the Zone 2 pit.

It should be noted that the results shown in MODFLOW model has a different orientation than the previous maps shown. Map overlays in the model have been rotated to show North at the top of the model and South at the bottom of the model.

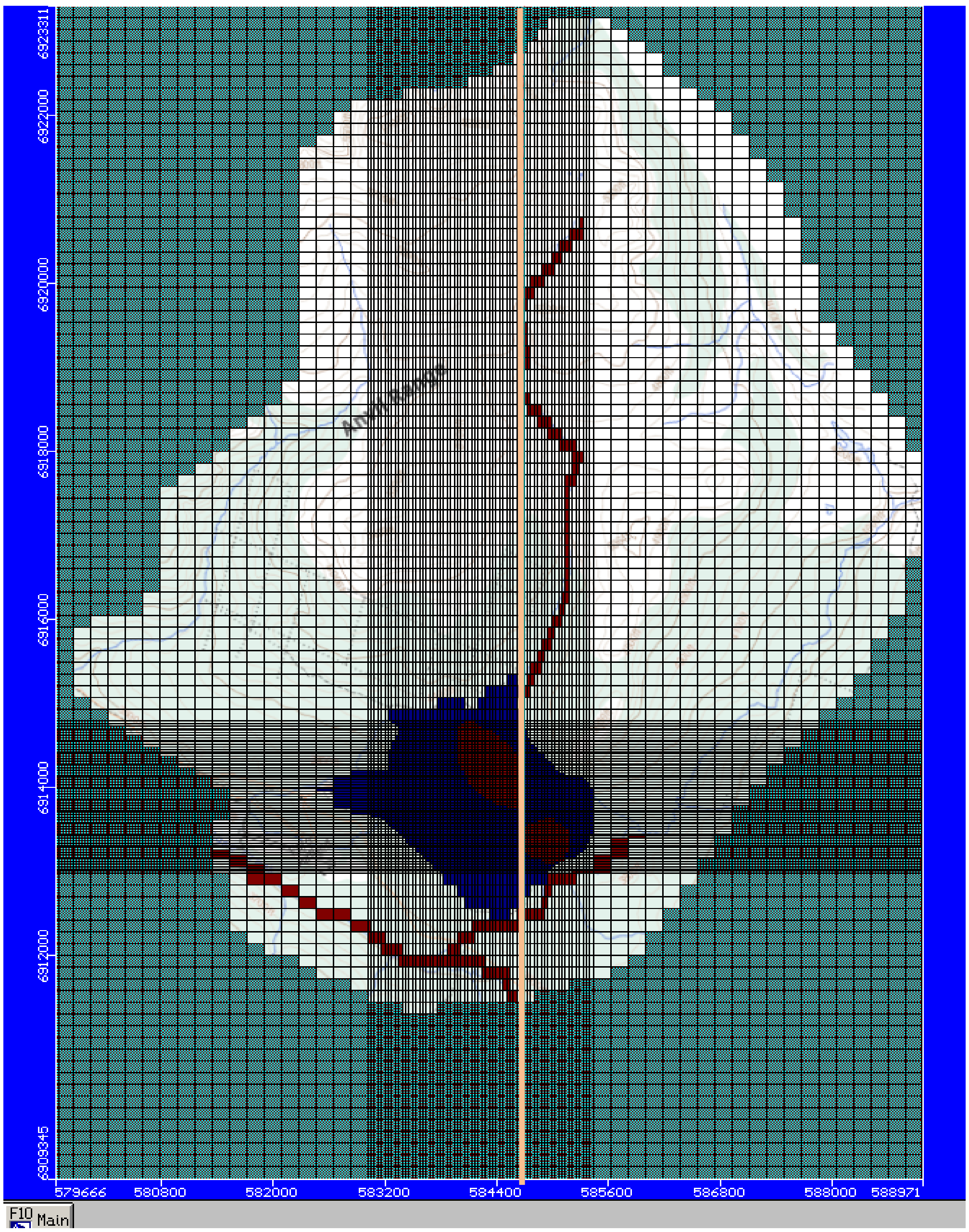

Figure 16. Location of column 64- line used for cross section

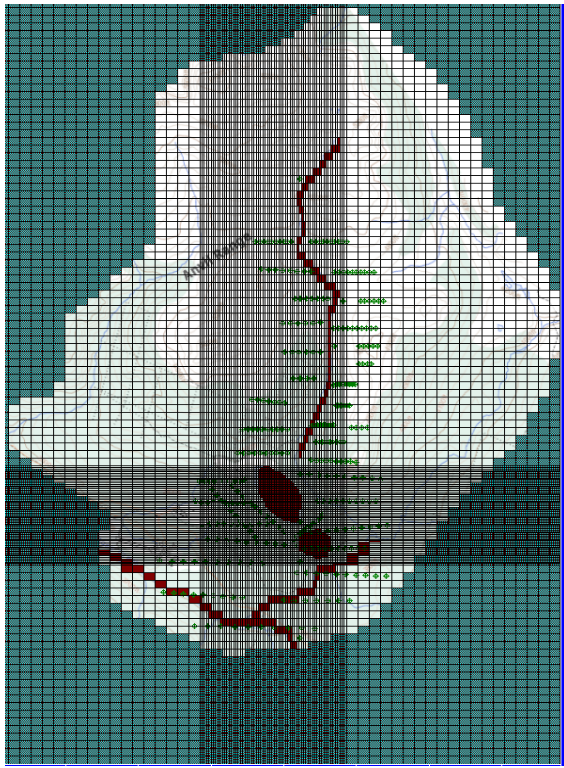

Figure 17. Locations of forward tracking particles in layer 1.

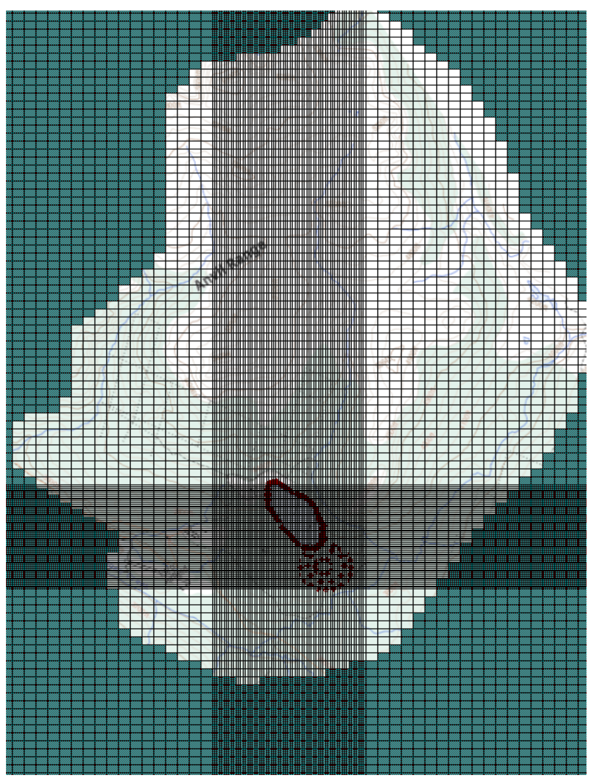

Figure 18. Locations of backward tracking particles outlining the main pit and the Zone 2 pit in layer 1.

4.0 Model Cases & Results

4.1 Case 1: Model Base Case

The base parameters for the model will be used for the first case. These parameters were obtained from data collected from published reports, and should represent the most current and ideal condition of the study area. The constant head of both pits are set to be 1110 m which represents a model that does not use Zone 2 pit as a hydraulic sink and all flow will go into the main pit (Roberson GeoConsultants, 1996a).

Hydraulic conductivities for all layers represent a homogeneous model where all X, Y, Z- direction have the same hydraulic conductivity. Layer 1 represents the overburden material with a hydraulic conductivity of $1x10^{-5}$ m/s. Layers 2 to 5 represent the meta-sedimentary layers and granite batholith which have a hydraulic conductivity of $7x10^{-8}$ m/s and $1x10^{-10}$ m/s respectively. A recharge rate of 208 mm/yr is used for the waste dumps and 63 mm/yr is used for the natural ground in this model.

Parameters used for Case 1 are summarized in Table 3.

Case 1		
Hydraulic conductivity (layer 1)	$K_{x,y,z}=1x10^{-5}$ m/s	
Hydraulic conductivity (layer 2-5 Blue)	$K_{x,y,z}=7x10^{-8}$ m/s	
Hydraulic conductivity (layer 2-5 Green)	$K_{x,y,z}=1x10^{-10}$ m/s	
Recharge	Waste dumps: 208 mm/year	Natural ground: 63 mm/year
Faro Main Pit constant head	1110 m	
Zone 2 pit constant head	1110 m	

Table 3. Model input parameters for Case 1

4.1.1 Case 1 Results

The forward and backward model results for Case 1 (Figure 19, Figure 20) indicate groundwater capture in both the main pit and the Zone 2 pit. Groundwater is calculated to have captured groundwater flow from west side of Faro Creek. There are well-developed capture zones mainly around the main pit and to a lesser amount in Zone 2 pit. Most of the groundwater flow to the east of the Faro Creek is captured by the main pit with a small portion diverted to the Zone 2 pit. About 50% of the waste rock dumps are in the vicinity of the capture zone and the groundwater is captured by the north-west and eastern side of the main pit and north-east side of the Zone 2 pit. Groundwater that bypasses the main pit and the Zone 2 pit are discharged at the Rose Creek down gradient. To the north of the model, the groundwater is most likely to be discharged in to the Faro Creek because it is not affected by the pits to the south and follow natural flow paths dictated by topography. The discharge into Faro Creek creates “circular” flow paths to the north of the model. Areas that are part of the mountains of Anvil Range and are highly elevated, tan-coloured spots are visible. These tan-coloured spots represent dry areas.

In cross sectional view, particles that were placed with depth (Figure 21) indicates deep groundwater in the meta-sedimentary layer will converge and flow along contact of the batholith and discharged at the Rose Creek. Groundwater that is drawn to the surface is captured mainly by the main pit shown with a more defined capture zone. The Zone 2 pit does not show a well-defined capture zone, meaning groundwater is not effectively captured or bypasses the pit. To the south of the Zone 2 pit, less confined flow paths indicate groundwater is not constrained to a path and is discharged into the North Fork of Rose Creek when not captured by the Zone 2 pit. Generally, groundwater flow is not affected by the Faro Creek and the Rose Creek and has a higher chance of being captured by the main pit.

Particles released in the first layer (Figure 22) to simulate surface recharge, indicated that majority of surficial water are contained in the same layer (overburden material). Some of the shallow groundwater are found to travel down to the meta-sedimentary layer and are later drawn back up to the first layer later down the flow path.

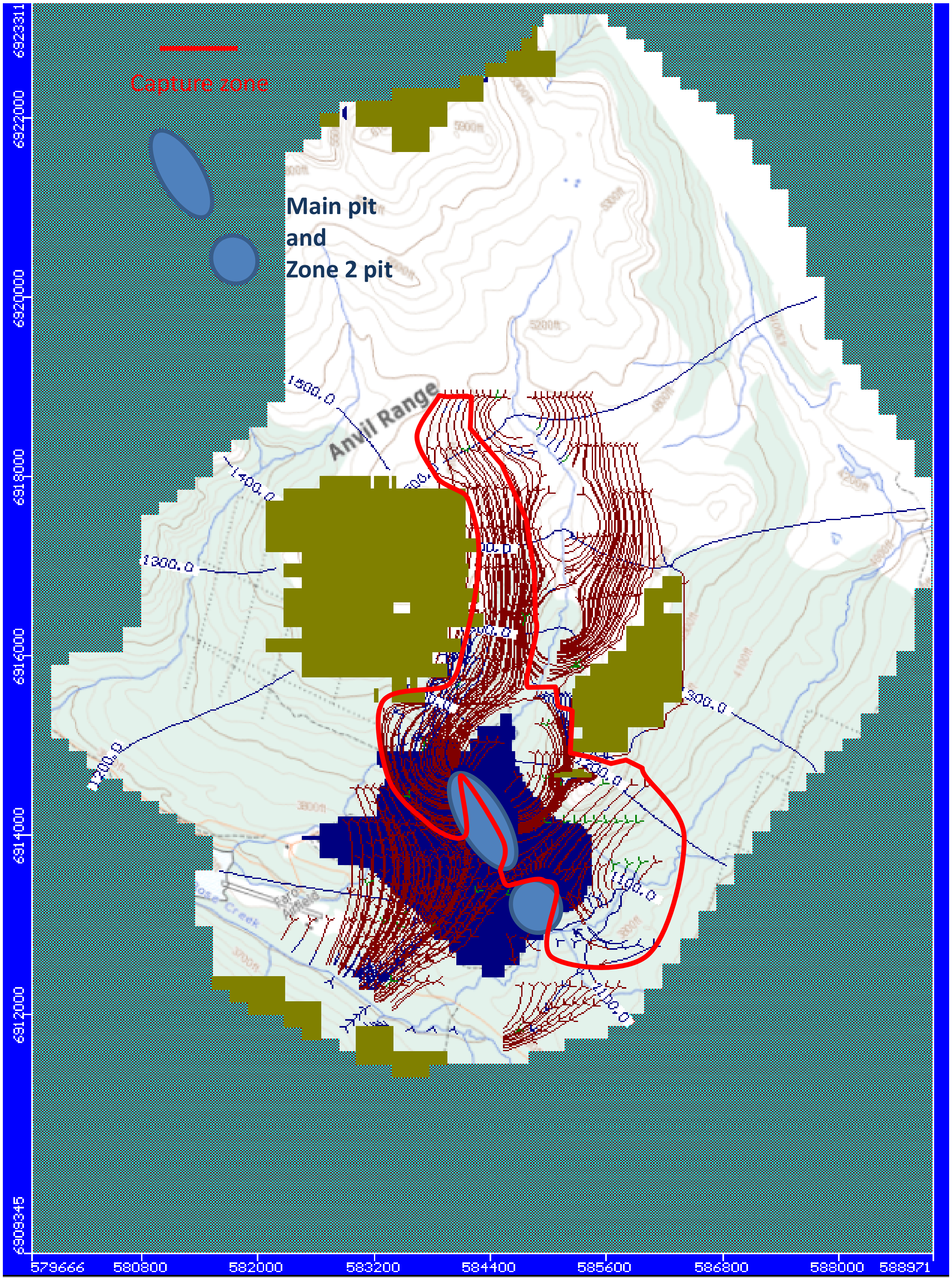

Figure 19. Forward capture zone model for Case 1

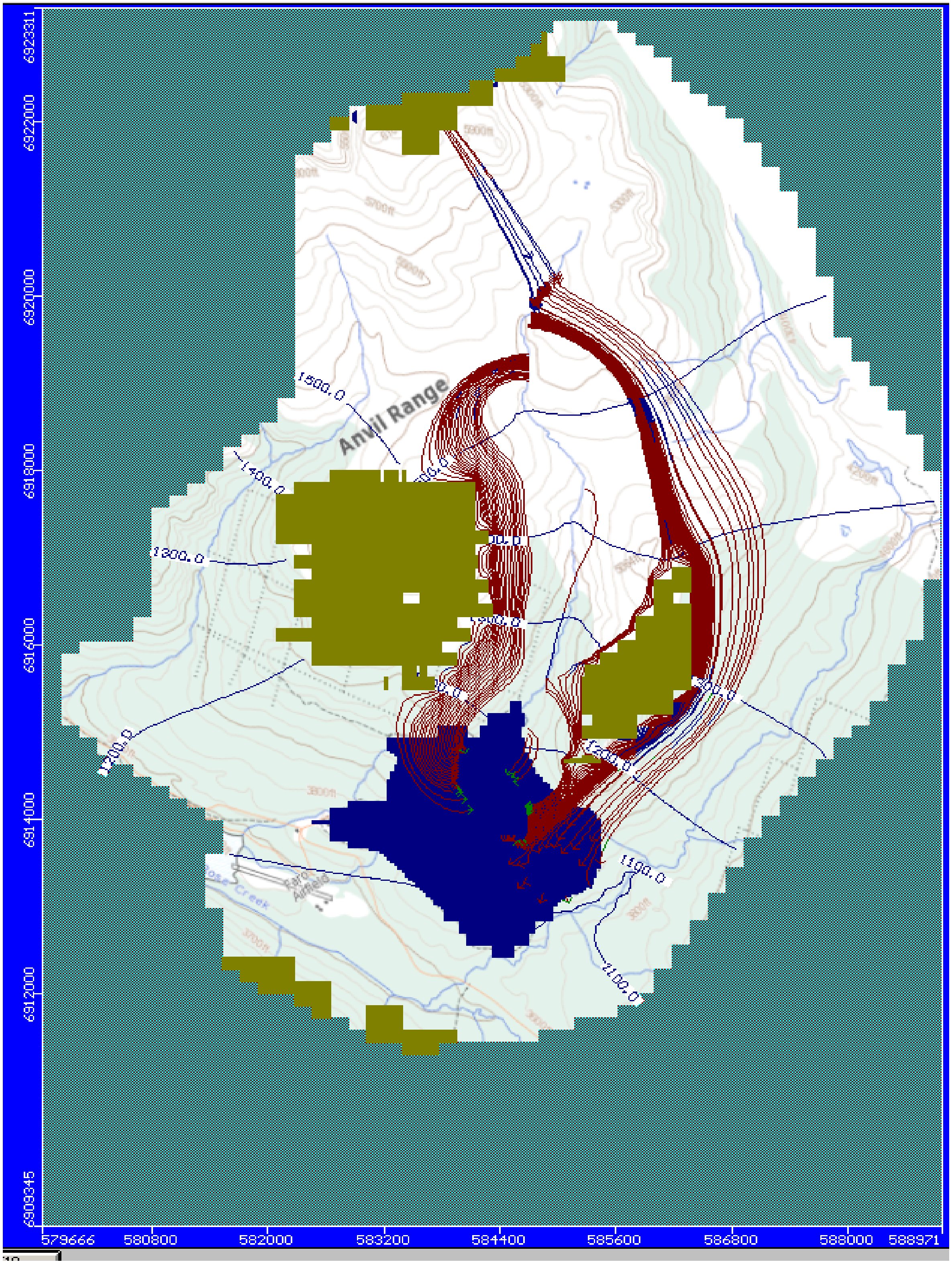

Figure 20. Backward capture zone model for Case 1

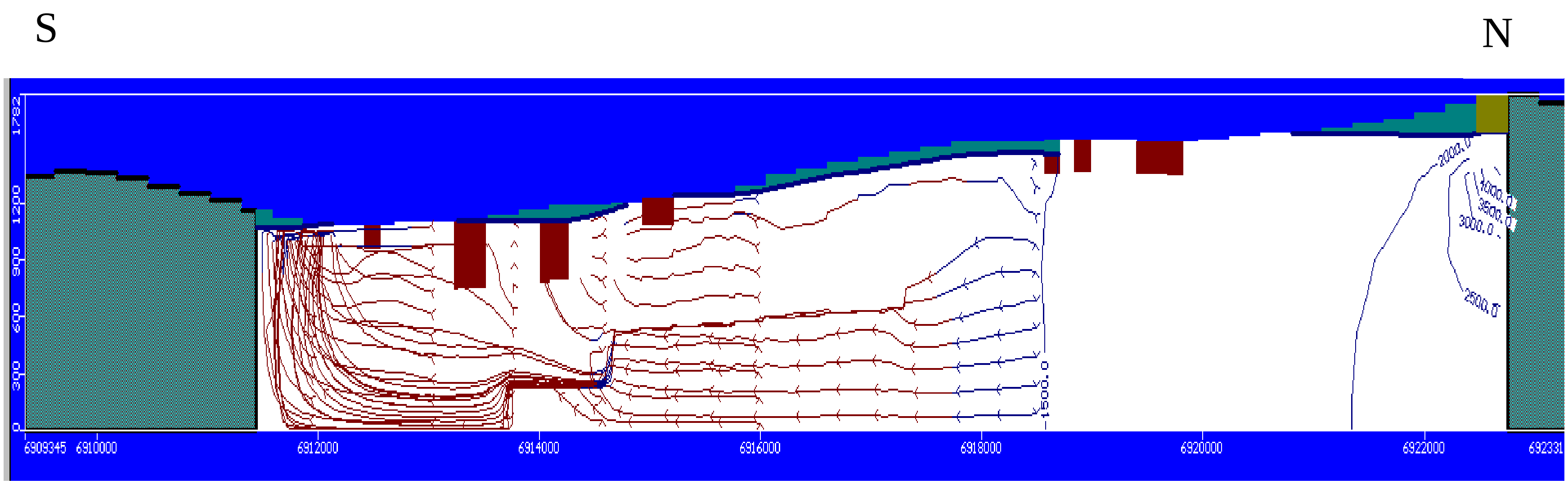

Figure 21. Cross section capture zone model for Case 1 for particle flow with depth

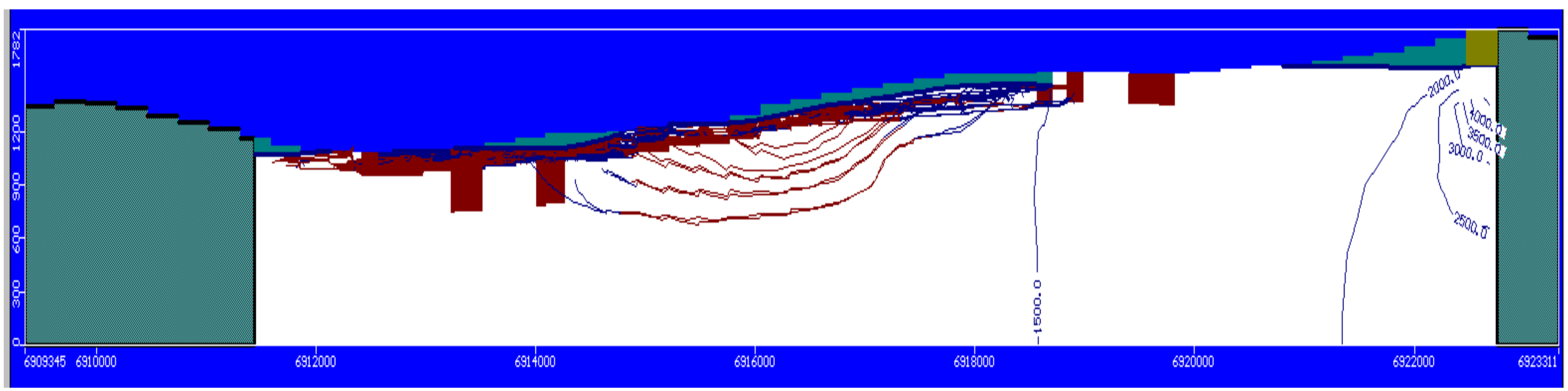

Figure 22 Cross section capture zone model for Case 1 for particles in layer 1

4.2 Case 2: Elevated Constant Head Value at Faro Mine Main Pit

For a more realistic model, we will need to apply the current water level that is at the main pit. The water level at the main pit is currently maintained at 1143 m which results in a hydraulic head difference with Zone 2 pit. This change will create a cone of depression between the main pit and the North Fork of Rose Creek and trigger seepage from the main pit to the Zone 2 pit (Robertson GeoConsultants, 1996a). With all other parameters equal to Case 1, increasing only the hydraulic head of the main pit will provide a better understanding of how a difference in hydraulic head between the main pit and the Zone 2 pit will affect the capture zone. Upcoming cases in this thesis will continue to use 1143 m as the main pit constant head value for a more representative model.

Case 2	
Hydraulic conductivity (layer 1)	$K_{x,y,z}$ =1x10^{-5} m/s
Hydraulic conductivity (layer 2-5 Blue)	$K_{x,y,z}$ =7x10^{-8} m/s
Hydraulic conductivity (layer 2-5 Green)	$K_{x,y,z}$ =1x10^{-10} m/s
Recharge	Waste dumps: Natural ground: 208 mm/year 63 mm/year
Faro Mine main Pit constant head	1143 m
Zone 2 pit constant head	1110 m

Table 4. Model input parameters for Case 2.

4.2.1 Case 2 Results

In this model, the main pit constant head was increased. This increase of constant head affected the capture zone around the main pit. Capture zone in the north-west side of the main pit has decreased (

Figure 23 & Figure 24), and more groundwater flow has been diverted to be discharged at Rose Creek. Compared to Case 1, a portion of the north-west side of the main pit is not active in capturing any groundwater flow. This change has increased capture zone at Zone 2 pit dramatically, and most groundwater in the vicinity of Zone 2 pit is effectively captured, especially the north-west portion of Zone 2 pit which was not captured in Case 1(Figure 24) . The area of waste rock dumps that lie within the capture zone has decrease and is now only 35%.

Deep water groundwater flow indicates (Figure 25) a more defined and deeper Zone 2 pit capture zone. This ultimately decreased the discharge at North Fork of Rose Creek since flow is captured by the Zone 2 pit. Deep groundwater flow is also more concentrated at the contact between the meta-sedimentary layer and the granite batholith. Surficial water (Figure 26) showed a change in that deeper water is bypassing the two pits and discharging into Rose Creek.

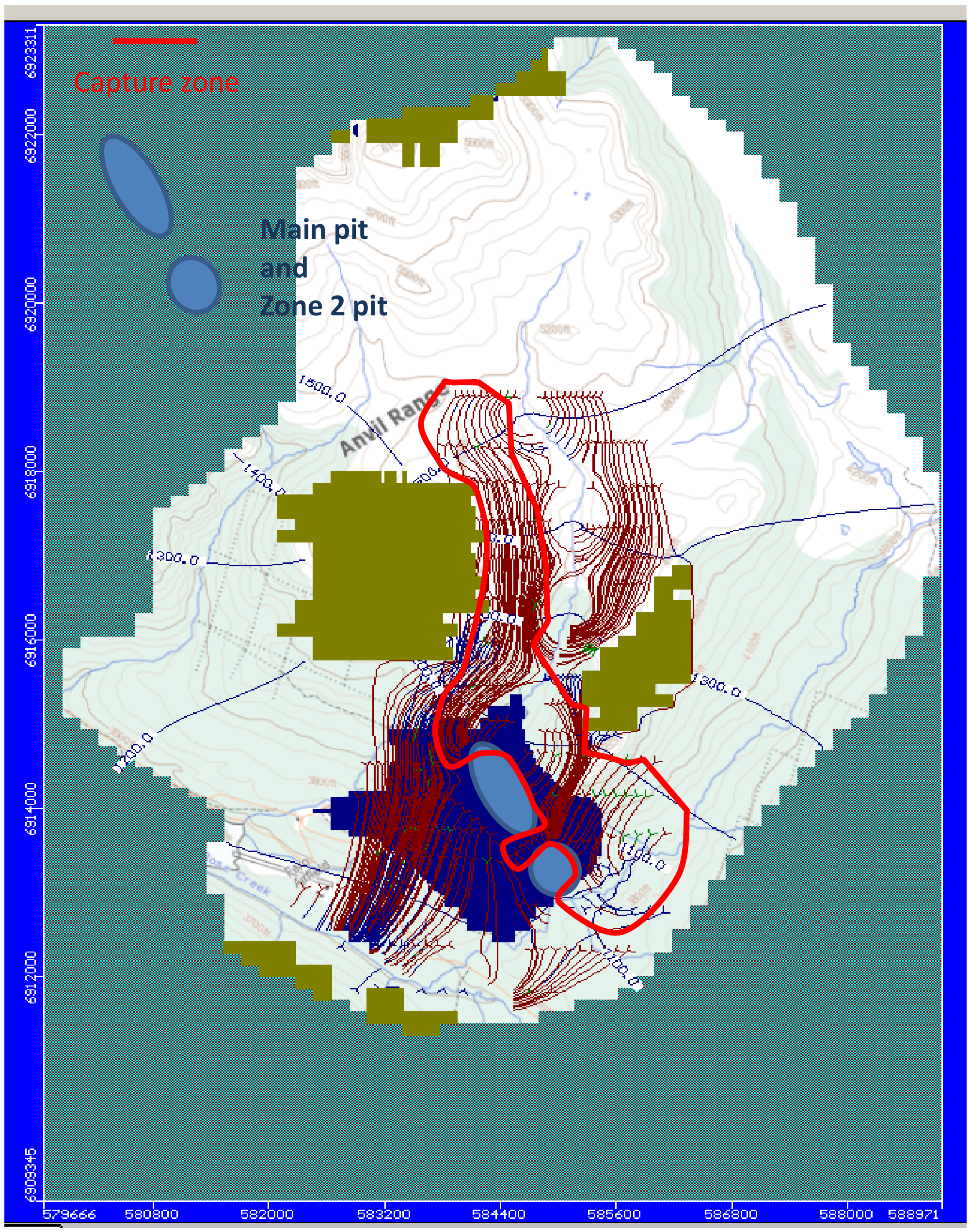

Figure 23. Forward capture zone model for Case 2

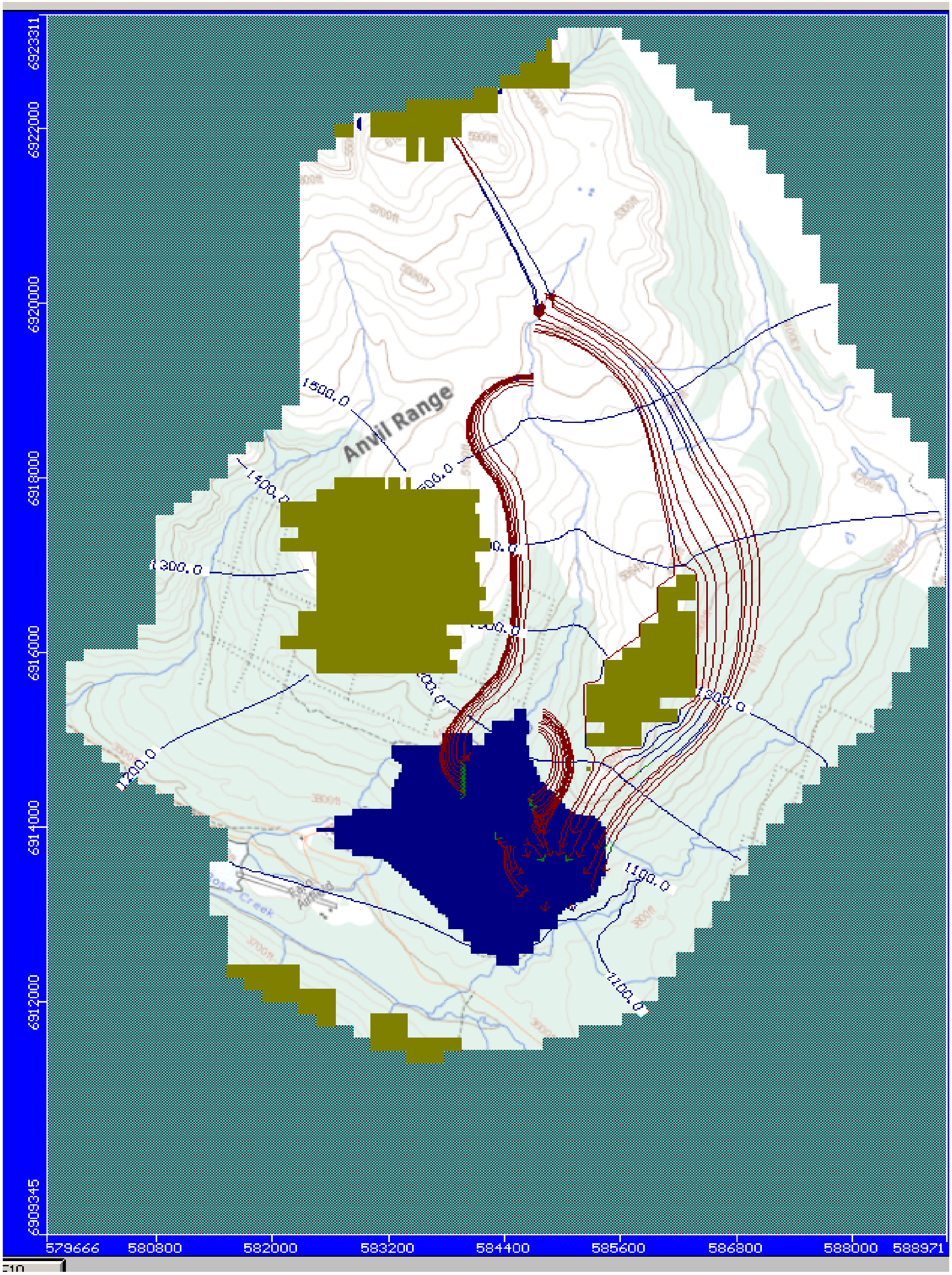

Figure 24. Backward capture zone model for Case 2

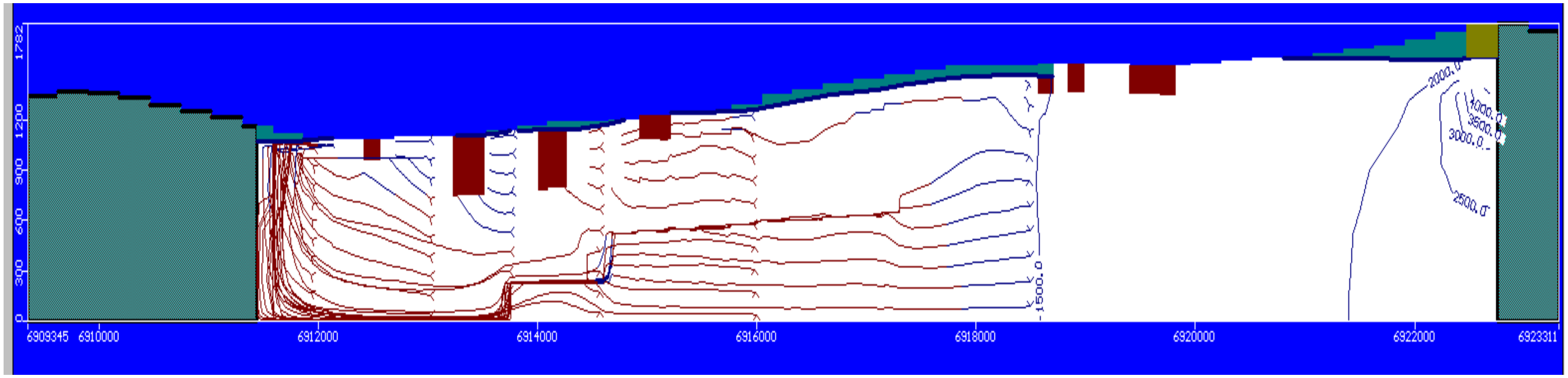

Figure 25. Cross section capture zone model for Case 2 for particle flow with depth

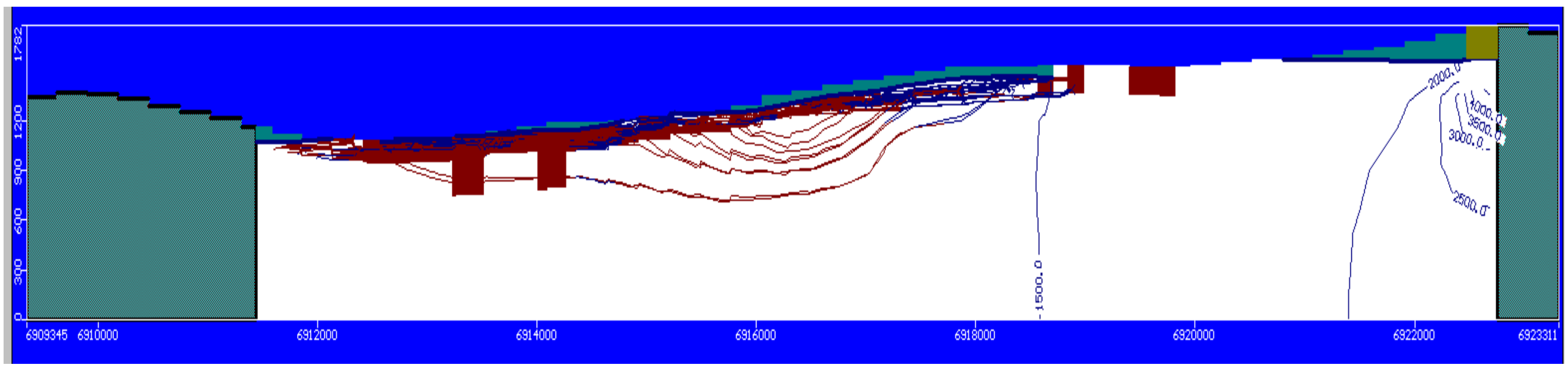

Figure 26. Cross section capture zone model for Case 2 for particles in layer 1

4.3 *Case 3: Increase in Recharge Rate*

As stated in previous sections, the recharge rate obtained from J.R. Janowicz et al. (2006) for this model was recorded to be the highest in 26 years. To understand how recharge rate can affect the capture zone, the recharge rate was increased to 150 mm/yr for Case 3. An increase recharge has been chosen because it can present a better understanding of how recharge can affect groundwater flow.

Case 3	
Hydraulic conductivity (layer 1)	$K_{x,y,z}$ =1x10^{-5} m/s
Hydraulic conductivity (layer 2-5 Blue)	$K_{x,y,z}$ =7x10^{-8} m/s
Hydraulic conductivity (layer 2-5 Green)	$K_{x,y,z}$ =1x10^{-10} m/s
Recharge	Waste dumps: 208 mm/year Natural ground: 150 mm/year
Faro Mine main Pit constant head	1143 m
Zone 2 pit constant head	1110 m

Table 5. Summary of parameter estimates for Case 3

4.3.1 *Case 3 Results*

Increasing the recharge rate did not show significant difference in the capture zone pattern (Figure 27 & Figure 28). Capture zone for the main pit is still limited in the north-west region with groundwater flow discharging into Rose Creek.

However, the cross section shows contour intervals have changed slightly from an increase in recharge rate, implying a less gradual gradient for groundwater flow (Figure 29). Deep water flow pattern had no significant changes compared to the original recharge. A distinct capture zone is still visible from discharge to the main pit and Zone 2 pit in the first layer and even down to the top of the meta-sedimentary layer. Shallow groundwater flow (Figure 30) is more confined to the top layer due with lesser amount of groundwater percolating into the meta-sedimentary layer from higher runoff with higher recharge rate.

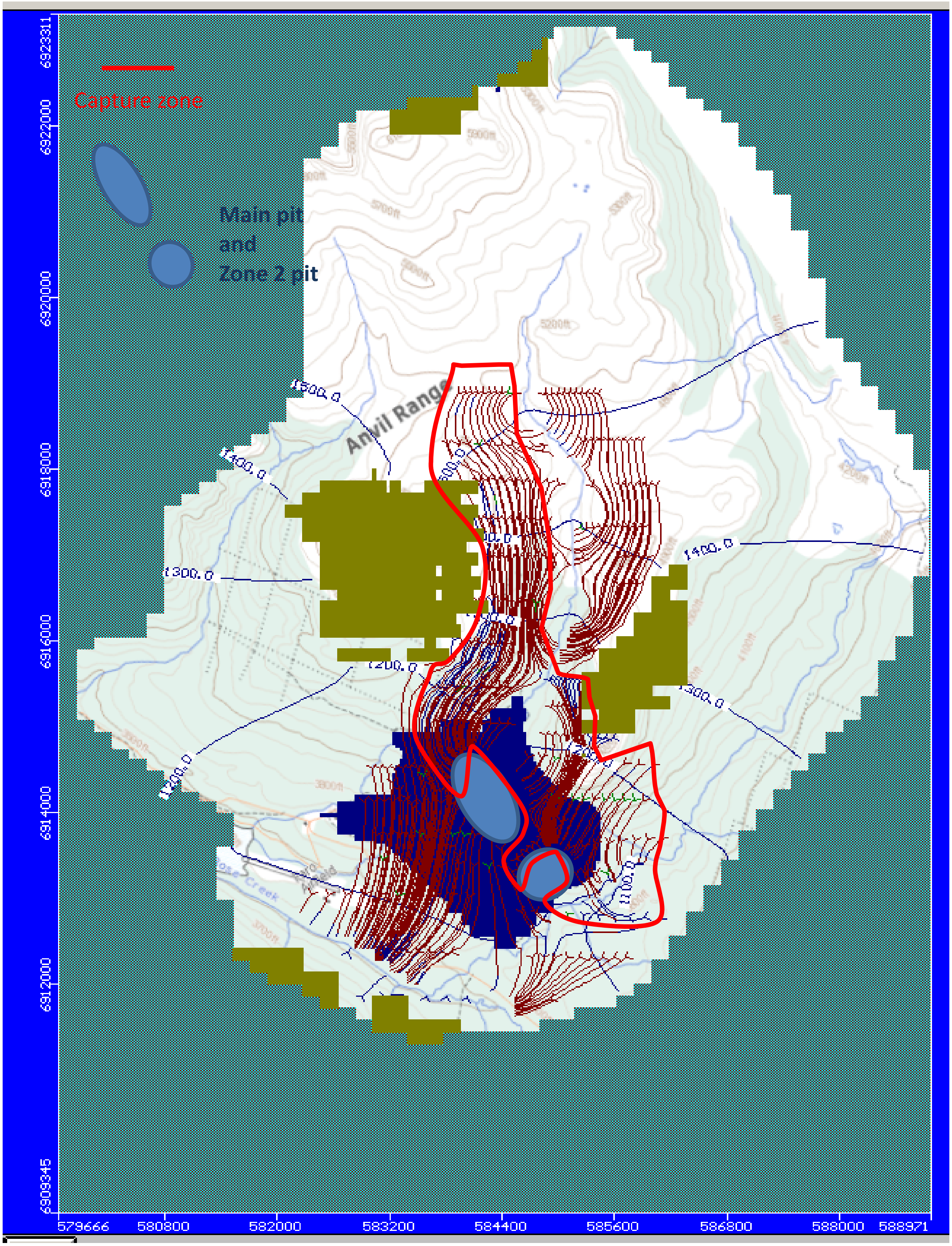

Figure 27. Forward capture zone model for Case 3

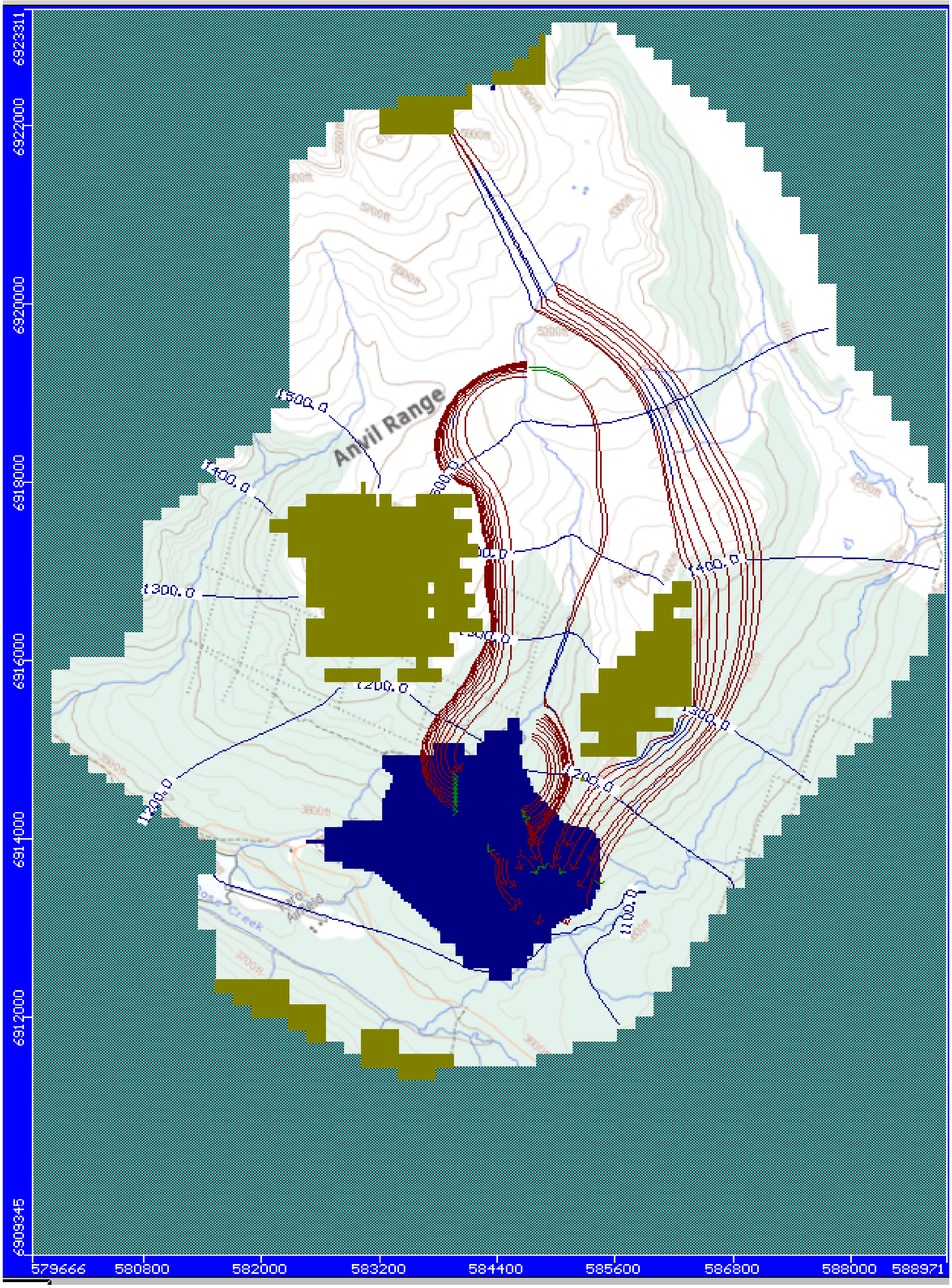

Figure 28. Backward capture zone model for Case 3

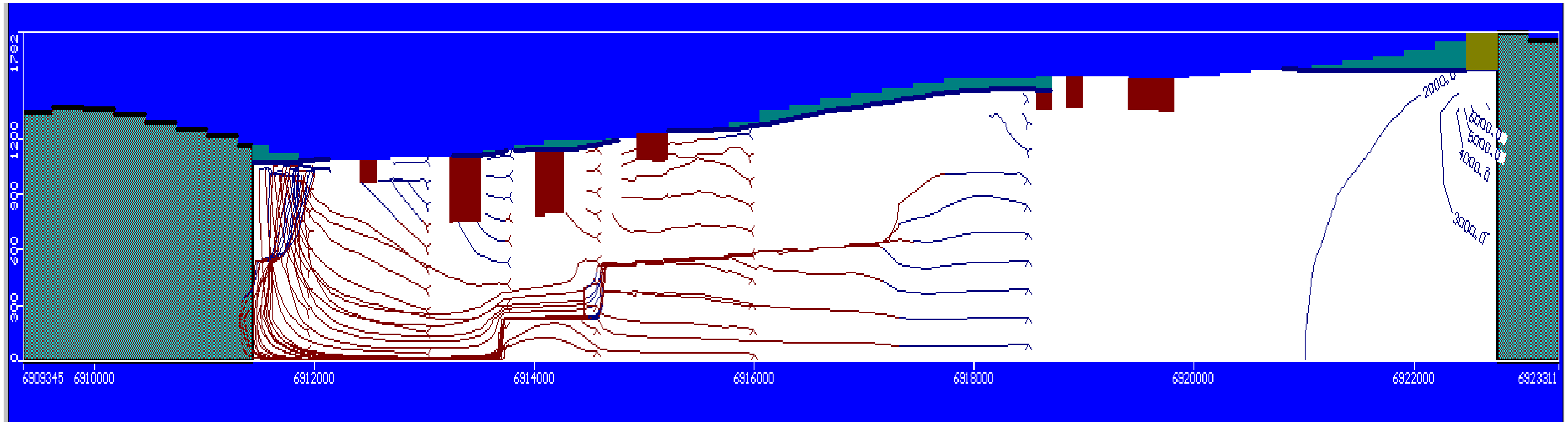

Figure 29. Cross section capture zone model for Case 3 for particle flow with depth

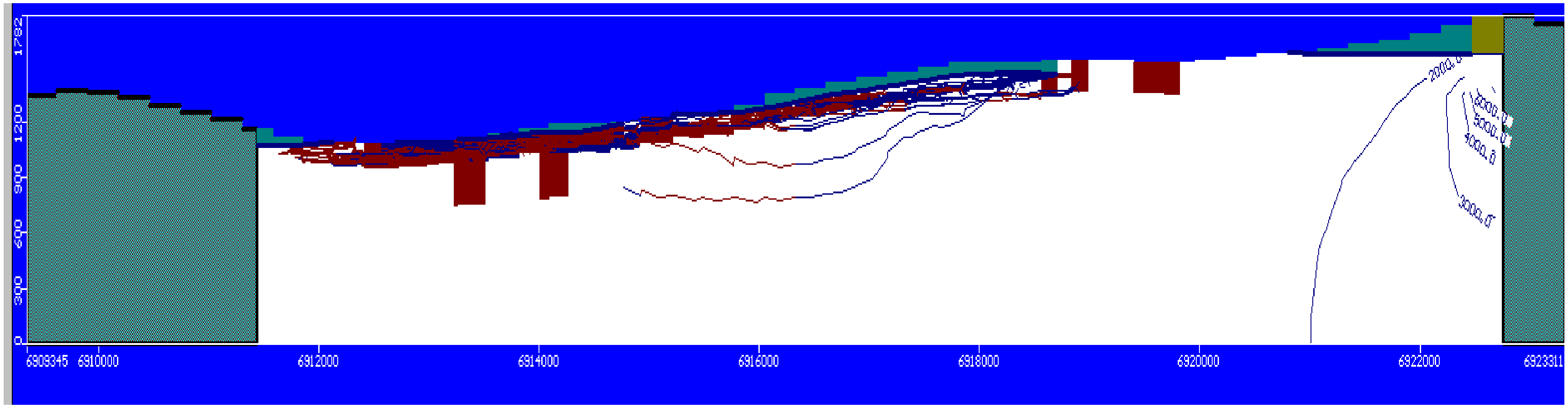

Figure 30. Cross section capture zone model for Case 3 for particles in layer 1

4.4 Case 4: Varying Hydraulic Conductivity – Low K Value

To further investigate how the capture zone is affected by varying parameters, hydraulic conductivities of the layers are most the important variables. Hydraulic conductivities of material will affect travel time and flow direction of groundwater. For this case, hydraulic conductivity will be decreased to simulate material with lower porosity which will have a higher resistance to flow. Only the hydraulic conductivity of the overburden material and the meta-sedimentary material are changed because the granite batholith does not play a big role in the groundwater flow system of this model.

Case 4	30 % decrease in hydraulic conductivity
Hydraulic conductivity (layer 1)	$K_{x,y,z} = 7x10^{-6}$ m/s
Hydraulic conductivity (layer 2-5 Blue)	$K_{x,y,z} = 5x10^{-8}$ m/s
Hydraulic conductivity (layer 2-5 Green)	$K_{x,y,z} = 1x10^{-10}$ m/s
Recharge	Waste dumps: 208 mm/year Natural ground: 63 mm/year
Faro Mine main Pit constant head	1143 m
Zone 2 pit constant head	1110 m

Table 6. Summary of parameter estimates for Case 4

4.4.1 Case 4 Results

Decreasing in hydraulic conductivity by 30% shows no significant changes to the aerial extent of the capture zone compared to previous models (Figure 31 & Figure 32). The forward and backward models show nearly identical results as the one present for Case 2.

In cross sectional view (Figure 33 & Figure 34), there is more concentrated flow along the batholith contact and groundwater prefers to along the contact, in the meta-sedimentary material. Shallow water flow shows a deeper seepage depth in the meta-sedimentary layer.

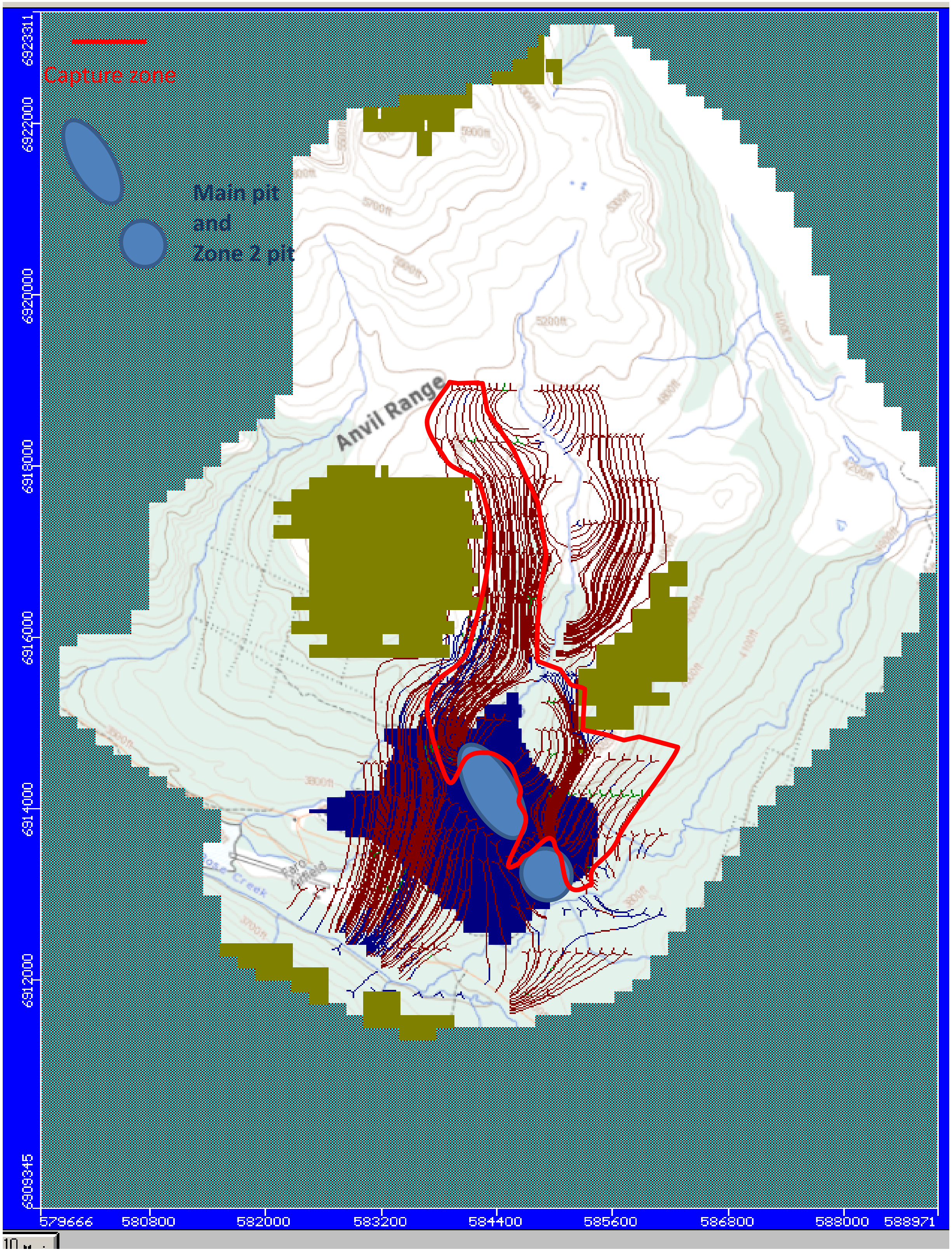

Figure 31. Forward capture zone model for Case 4

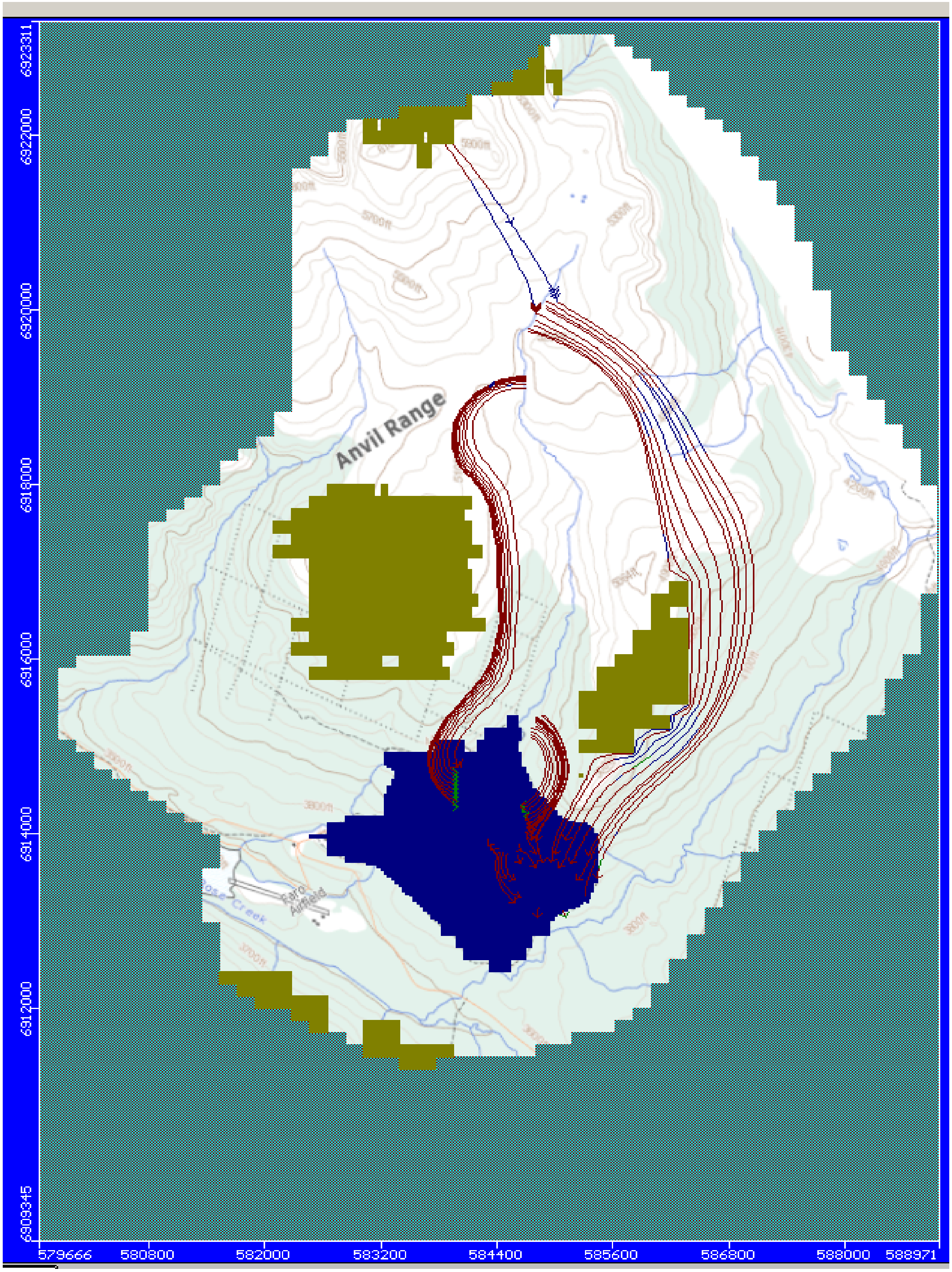

Figure 32. Backward capture zone model for Case 4

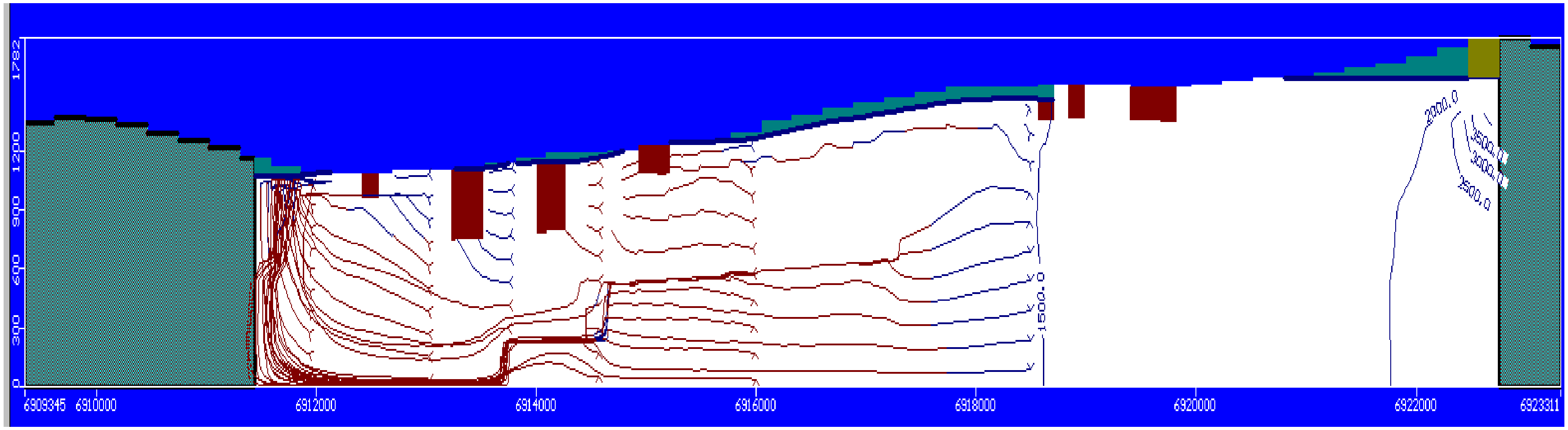

Figure 33. Cross section capture zone model for Case 4 for particle flow with depth

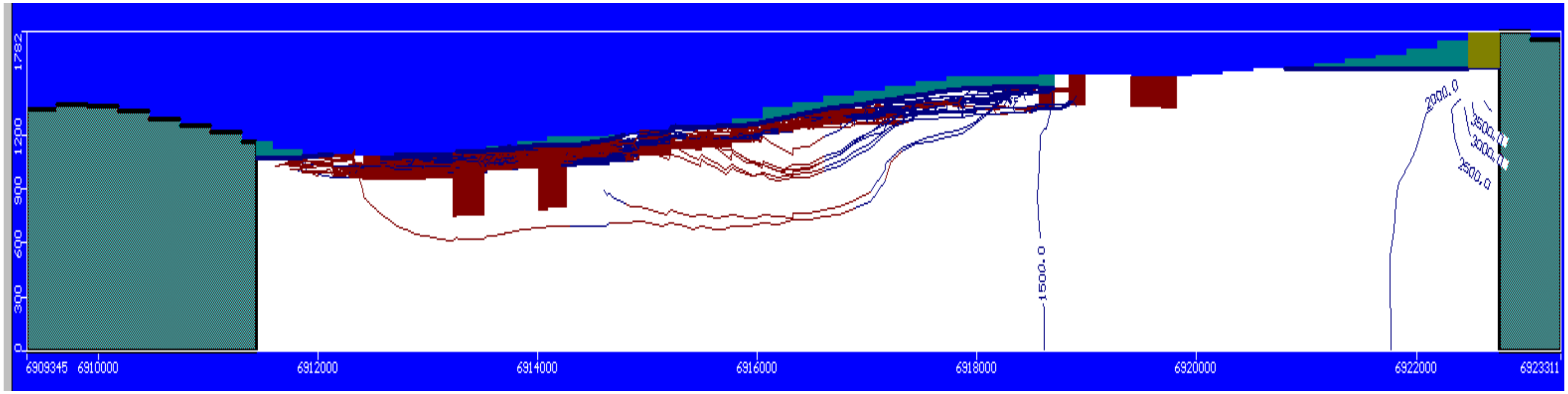

Figure 34. Cross section capture zone model for Case 4 for particles in layer 1

4.5 Case 5: Varying Hydraulic Conductivity- High K Value

Similar to Case 4, the hydraulic conductivity will now be increased for this case. Increase in the hydraulic conductivity is to simulate material with higher porosity which will have a lower resistance to flow.

Case 5	30% increase in hydraulic conductivity
Hydraulic conductivity (layer 1)	Kx,y,z=1.3 x10^{-5} m/s
Hydraulic conductivity (layer 2-5 Blue)	Kx,y,z=9 x10^{-8} m/s
Hydraulic conductivity (layer 2-5 Green)	Kx,y,z=1 x10^{-10} m/s
Recharge	Waste dumps: 208 mm/year / Natural ground: 63 mm/year
Faro Mine main Pit constant head	1143 m
Zone 2 pit constant head	1110 m

Table 7. Summary of parameter estimates for Case 5

4.5.1 Case 5 Results

The capture zone in the aerial extent is slightly affected by increasing hydraulic conductivity by 30%. In both the forward and backward models (Figure 35 & Figure 36) flow patterns display a similar result as Case 2 and have little change to its groundwater flow. With more porous material, groundwater is most likely to bypass the north-west section for the main pit and discharge into Rose Creek. This is illustrated in the backward model by having a narrower flow path towards the north-west section of the main pit, indicating decreased capture of groundwater.

Changing the hydraulic conductivity had little effect on the model. Deep groundwater in this Case indicates greater flow along the contact of the meta-sedimentary material and the granite batholith (Figure 37) due to ease of flow in material to reach the bottom of the meta-sedimentary layer. This is evident by having less flow path lines in the meta-sedimentary material and a greater outline of the granite batholith layer with flow path lines. Capture zones of the main pit and the Zone 2 pit are more prominent and capture water from greater depth. More concentrated flow at North Fork of Rose Creek also indicates greater discharge at the creek. Shallow groundwater (Figure 38) shows little change in flow pattern but have a deeper seepage in the meta-sedimentary layer also due to ease of flow resulting from higher hydraulic conductivity.

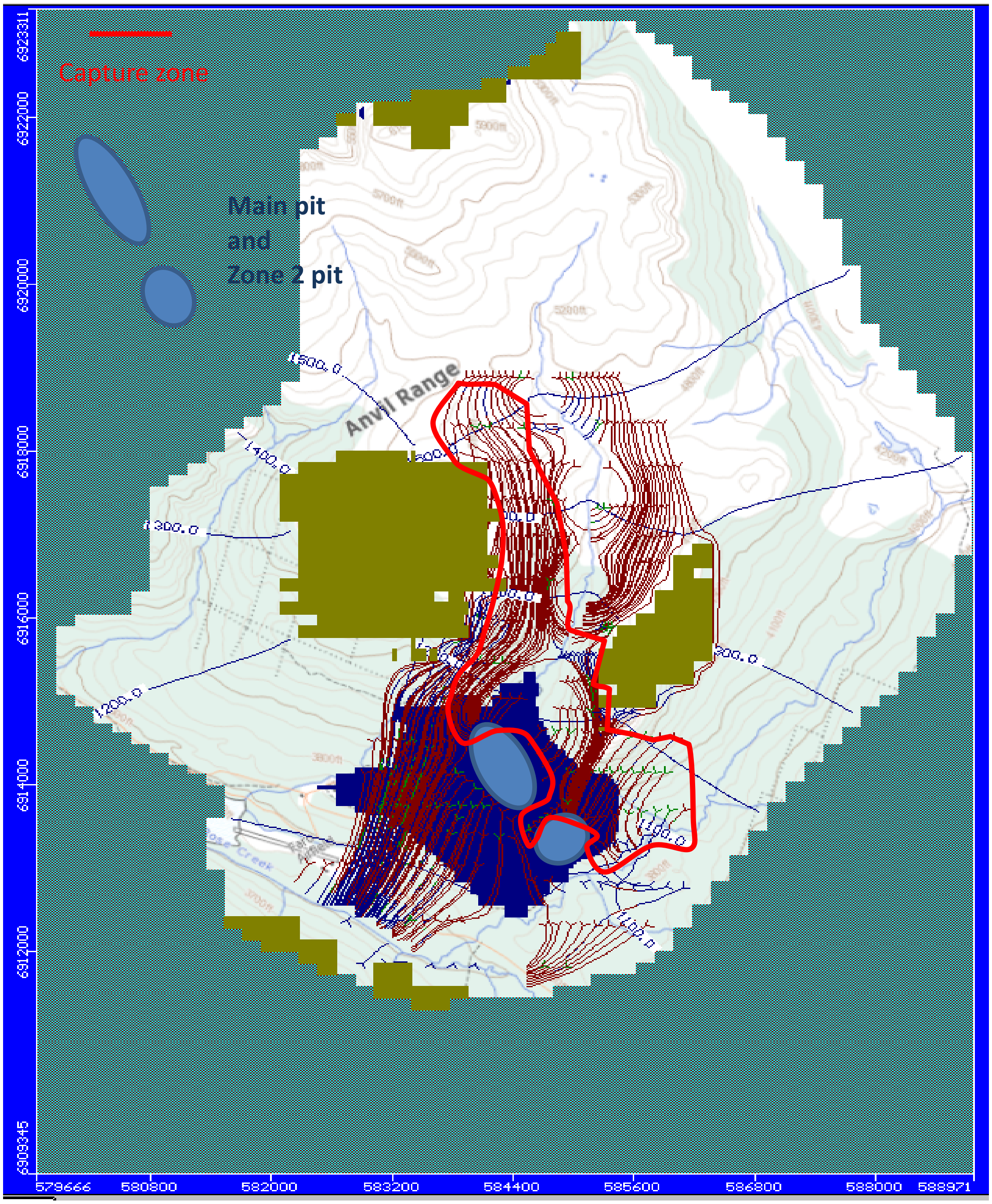

Figure 35. Forward capture zone model for Case 5

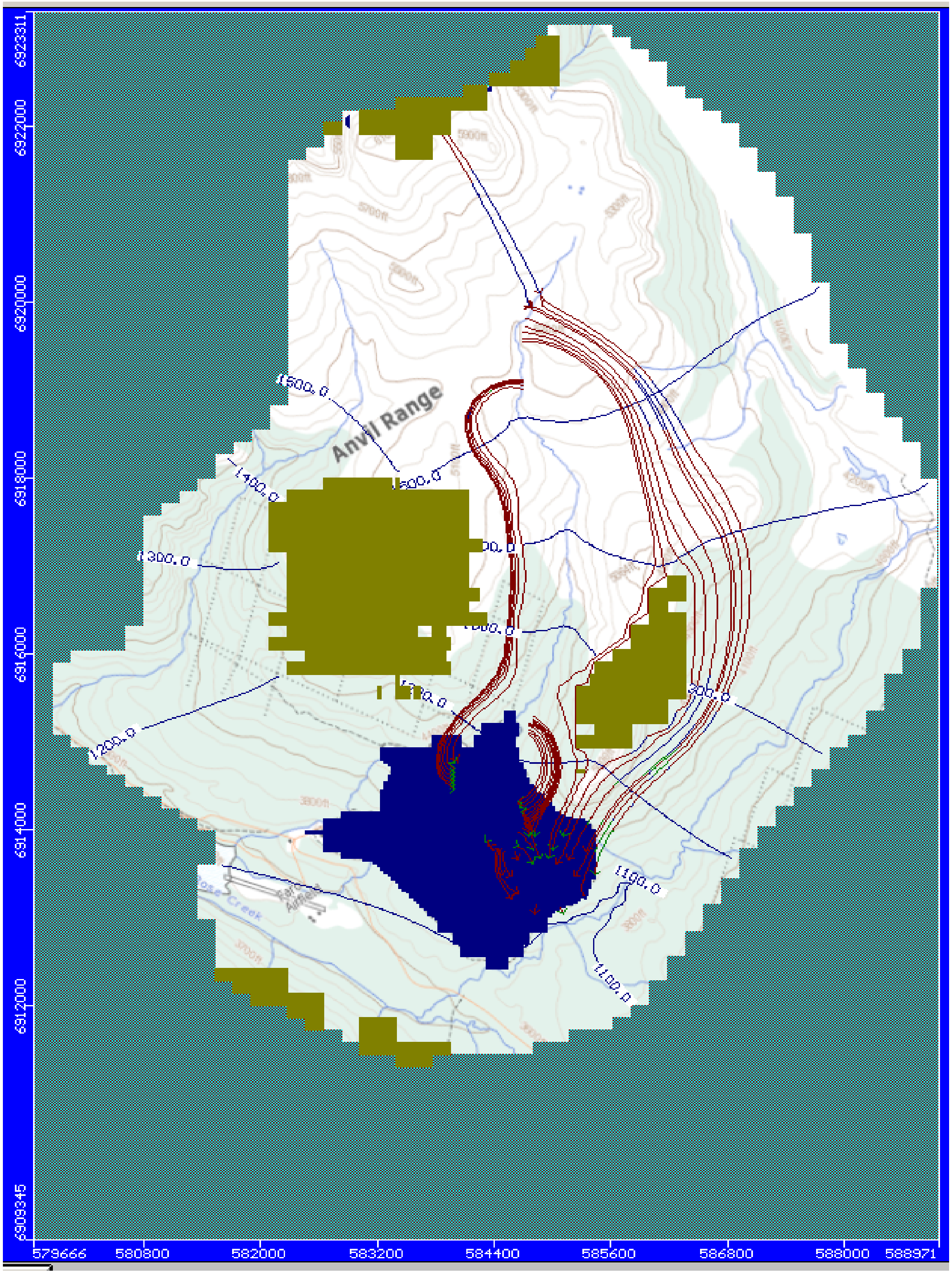

Figure 36. Backward capture zone model for Case 5

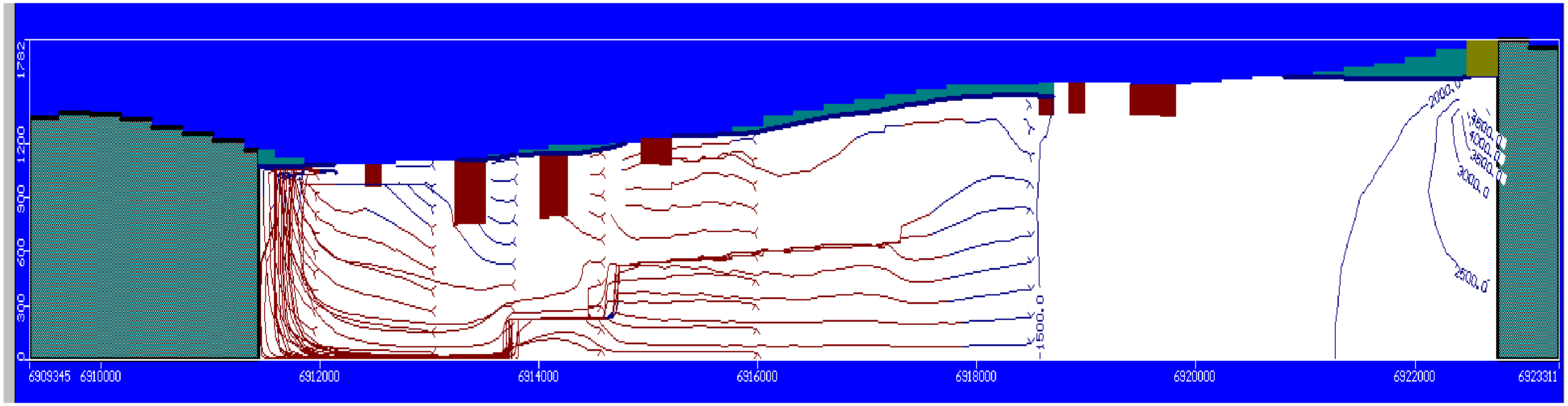

Figure 37. Cross section capture zone model for Case 5 for particle flow with depth

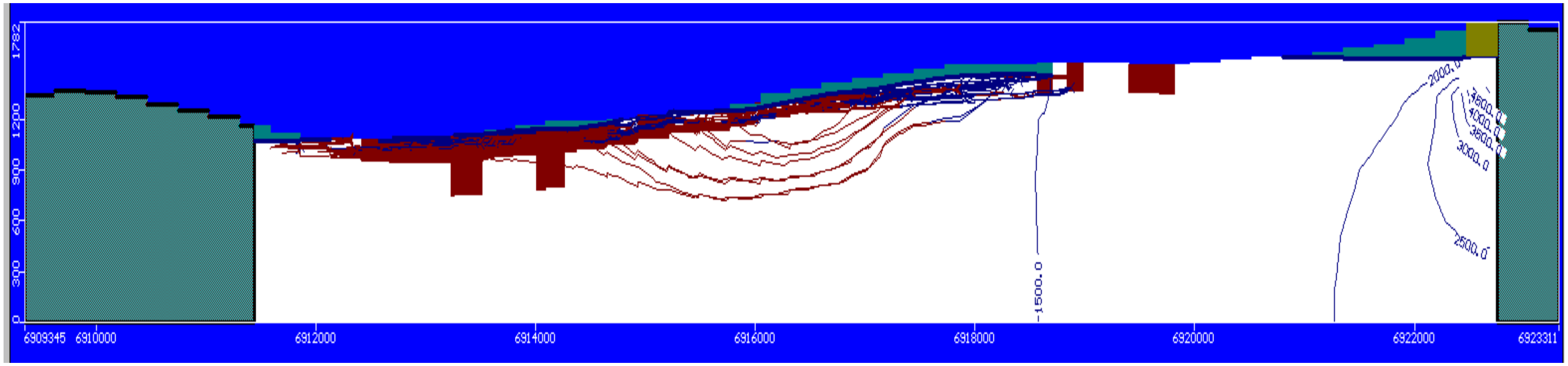

Figure 38. Cross section capture zone model for Case 5 for particles in layer 1

5.0 Discussions and Summary

5.1 Discussion

In the five cases tested, the most representative model would be that of Case 2 for the Faro Mine. It depicts a system that is current with an updated higher constant head at the main pit. Case 2 model is therefore used as the "base model" for further Cases.

From the results obtained, we can conclude that the most important parameter that changed the overall flow pattern of the capture zone was the constant head of the main pit in Case 2. Other parameters used to vary the model were not sensitive and resulted in insignificant change to the estimated capture zone in Cases 3 to 5. With increased water level in the main pit, capture zone area of main pit decreased to 35% from 50% in Case 1. As a result the north-west section of the main pit was no longer included in the capture zone. This can be explained by the decreased hydraulic gradient (where water travels from higher water level to lower water level) that would no longer attract water flow into the main pit. Instead, water travelling down gradient (to a lower water level) would have a greater driving force to discharge at a lower gradient (e.g. the Zone 2 pit at a lower constant head) than the main pit.

With the increase in constant head of the main pit affecting its capture zone in an aerial extent, the capture zone of the Zone 2 pit became more distinct in model results from Case 1 to Case 2. From Case 2 through 5, the Zone 2 pit no additional significant changes were noticed in the aerial extent.

It has been concluded from the three-dimension models that shallow groundwater is mostly confined in the overburden layer despite changes in constant head, recharge and hydraulic conductivity. This is mainly due to the lower hydraulic conductivity nature of the meta-sedimentary material. Common to all cases is that some of the shallow groundwater had travelled down to the meta-sedimentary layer and are later drawn back up to the first layer further down the flow path. This is a result of the natural characteristics of groundwater flow. Although shallow groundwater may travel down to the meta-sedimentary layer, groundwater that does tend to percolate into the meta-sedimentary layer is recharged from upstream from the north. No groundwater was shown to percolate from the waste dumps despite higher recharge rates.

For deep groundwater flow, it is evident that the main pit and Zone 2 pit are capable of capturing water to a depth of up to 400m and 650m respectively from Case 2 to 5. Beyond this depth, groundwater either flows along the contact of the granite batholith or flows at any depth of the meta-sedimentary layer to be discharged at the Rose Creek or other surface water down gradient. In Case 1 where the constant head of both pits are the same, the capture zone at depth is less defined for Zone 2. The main pit was evidently more favourable in capturing water than Zone 2 pit in Case 1 and resulted in groundwater bypassing Zone 2, showing a less defined capture zone. With the increase in constant head of the main pit, the Zone 2 pit capture zone was more well-defined because Zone 2 pit is capturing more effectively with a decreased capture capacity of the main pit.

From these results we come to understand that the natural water bodies like the Faro Creek do not affect the capture zone at depth. The North Fork of Rose Creek had minimal discharge once the water level of the main pit has been increased and with Zone 2 becoming the dominant capture zone. Groundwater that is neither captured nor discharged at the North Fork of Rose Creek is discharged at Rose Creek. We can conclude with these results that rising the water level in the main pit served as a positive solution for intercepting contaminated water that could seep into North Fork of Rose Creek because more groundwater was captured by the Zone 2 pit.

5.2 Conclusion

The ultimate purpose of this thesis was to investigate the portion of the waste rock piles that is within the capture zone and will be beneficial for capturing any contaminated water generated by the waste rock pile. Results have concluded that groundwater that extends into the meta-sedimentary layer is sourced from recharge in natural groundwater. Therefore, worries of contaminated groundwater seepage at depth from waste dumps can be eliminated. However, it can be seen that only 50% or less of the waste rock piles are within the capture zone, meaning further remediation actions needs to be taken to control contaminated water from infiltrating into the streams. This thesis proves that the natural topography is not sufficient in facilitating the remediation process.

5.3 Recommendation for Future Work

Calculations from these models gave a brief understanding of the effect of pit depressions on groundwater flow patterns. Although groundwater flow was well captured by the pits, the location of interest was not effectively captured. Effective capture zones were to the north-east of the main pit and Zone 2 pit, but the area of interest was to the south-west of the pits where the waste piles were located. If groundwater modelling of the pits were conducted prior to construction of the waste piles, location of the waste piles can be strategically located to accommodate groundwater capture in the pits.

In future mining projects, it is suggested that groundwater modelling procedures to be conducted prior to production. Delineating the groundwater flow and using that information for remediation planning can be beneficial for lowering costs and environmental problems that could arise.

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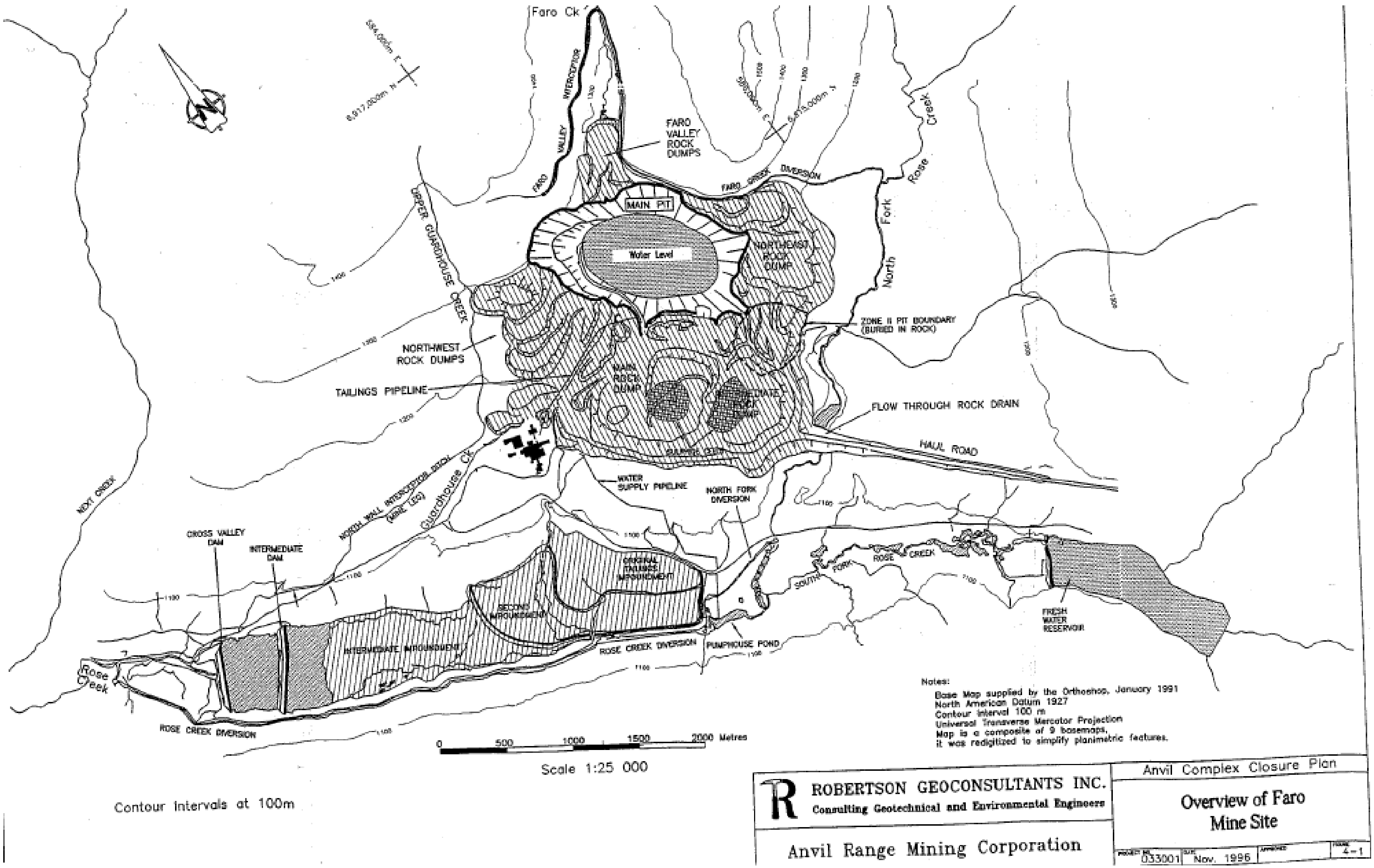
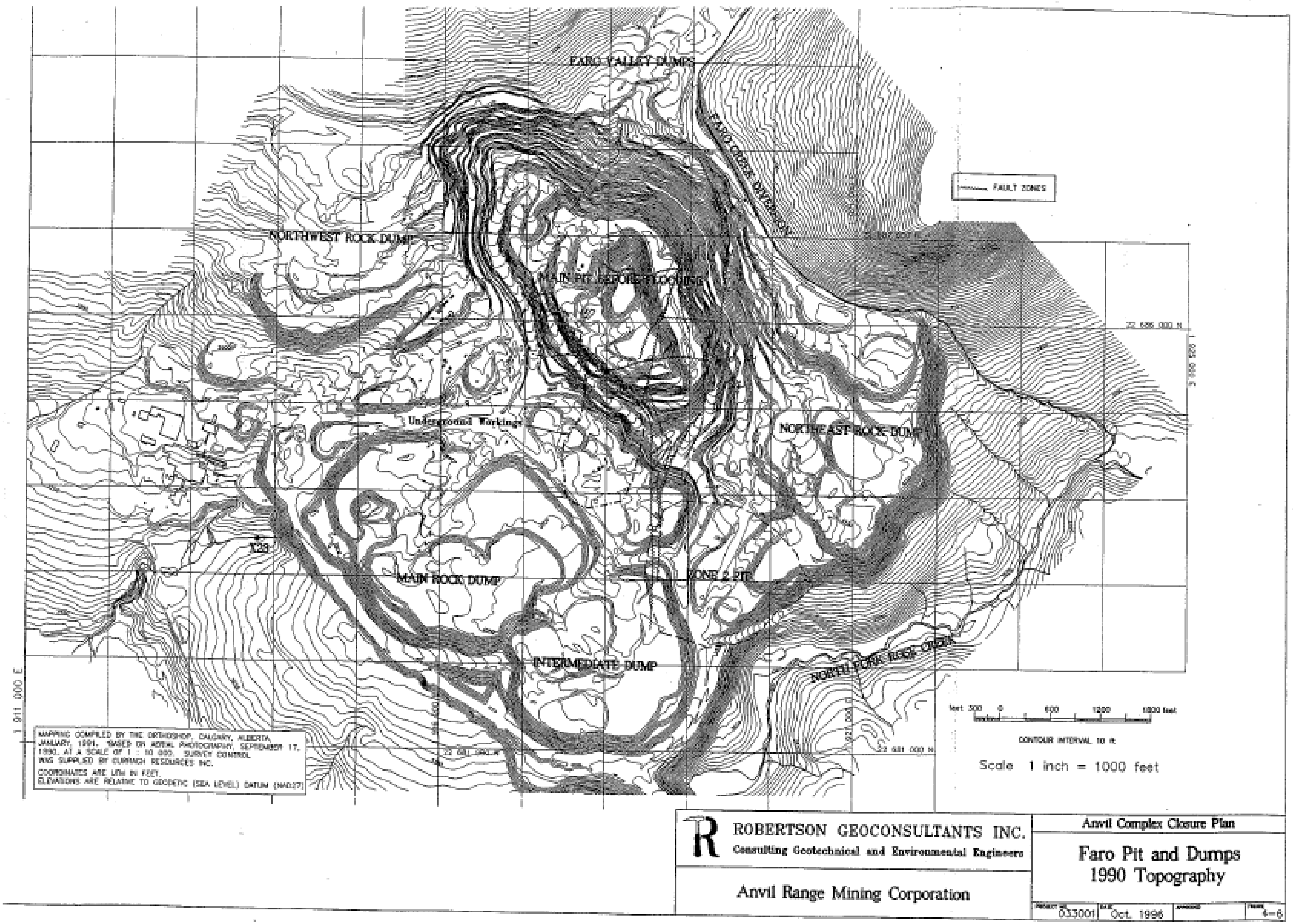
Appendix: Site Maps




FARO VALLEY DUMPS
FARO CREEK DIVERSION
FAULT ZONES
NORTHWEST ROCK DUMP
MAIN PIT BEFORE FLOODING
Underground Workings
NORTHEAST ROCK DUMP
MAIN ROCK DUMP
ZONE 2 PIT
INTERMEDIATE DUMP
NORTH FORK ROSE CREEK
CONTOUR INTERVAL 10 ft
Scale 1 inch = 1000 feet
COORDINATES ARE UTM IN FEET.
ELEVATIONS ARE RELATIVE TO GEODETIC (SEA LEVEL) DATUM (NAD27)
ROBERTSON GEOCONSULTANTS INC.
Consulting Geotechnical and Environmental Engineers
Anvil Range Mining Corporation
Anvil Complex Closure Plan
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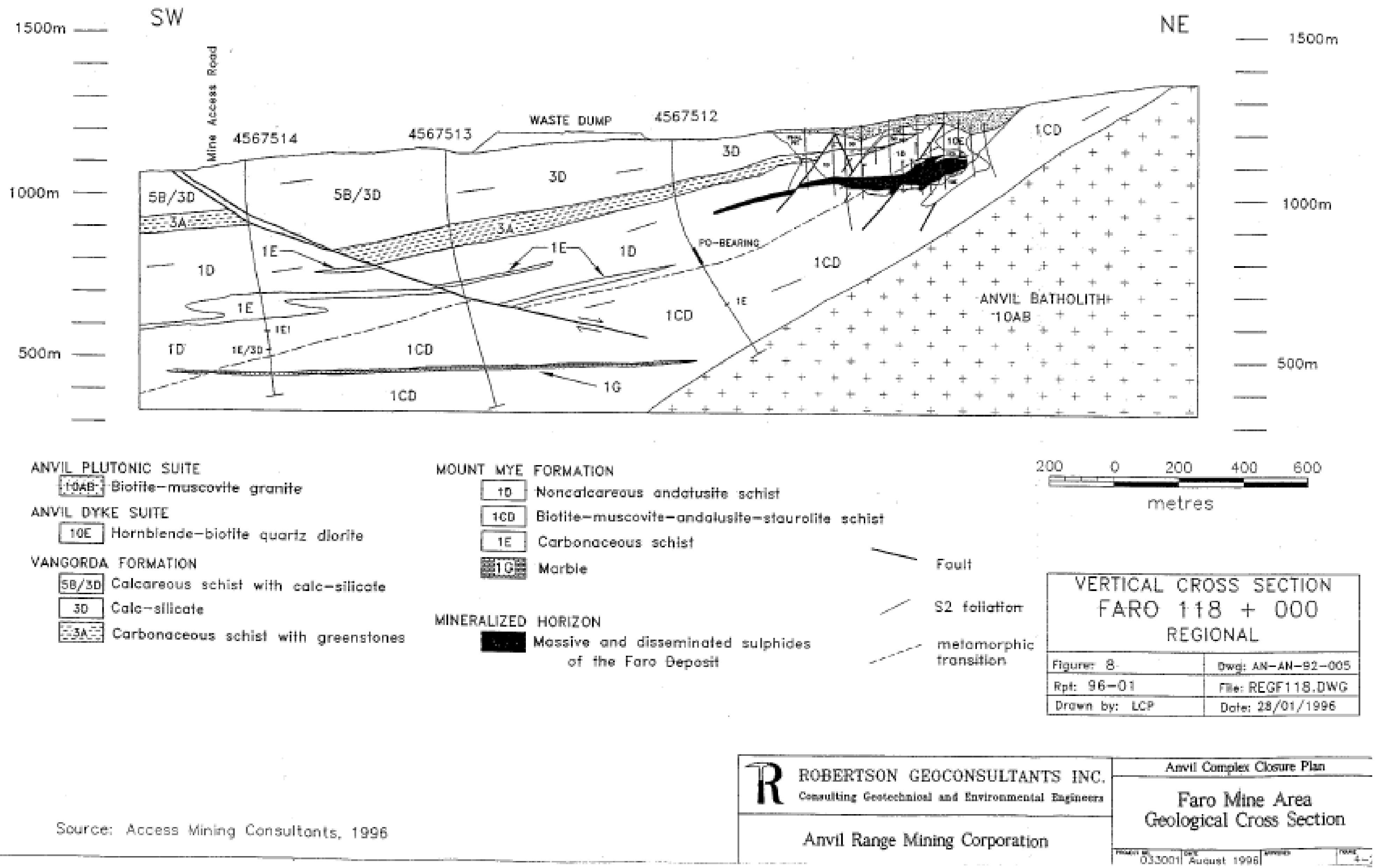
033001
Oct. 1996
4-6



Source: Access Mining Consultants, 1996