

**ACID DRAINAGE FROM MINE
WALLS: THE MAIN ZONE PIT AT
EQUITY SILVER MINES**

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This project was funded by Energy, Mines and Resources Canada and the British Columbia Ministry of Energy, Mines and Petroleum Resources under the Canada/British Columbia Mineral Development Agreement; and by Equity Silver Mines.

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PROJECT SUMMARY

ACID DRAINAGE FROM MINE WALLS:

THE MAIN ZONE PIT AT EQUITY SILVER MINES

At a minesite, acid drainage can develop in several mine components, including waste rock, tailings, and mine walls. Due to the more prevalent lack of information on mine walls, this study was conducted with four specific tasks in mind. The completion of these tasks has lead to a more detailed understanding of acid drainage from mine walls.

Firstly, a detailed literature review identified relevant information on the generation of acid and its migration in various modes of water movement. The information on water movement showed that mines can have hydrogeologic impacts to distances of tens of kilometers. The reviewed information on acid generation indicated that accumulation of acidity in unsaturated fractures could cause acidic conditions to develop within a pit during flooding.

The second task was a detailed evaluation of information related to acid generation, acid neutralization, metal leaching, and water movement at Equity Silver Mines, focussing on the Main Zone Pit. This evaluation highlighted the locations in the pit which are generating or will eventually generate net acidity as well as the locations which are not expected to generate net acidity at any time. The short-term monitoring of limited portions of the pit walls indicated the average rate of acid generation was 11 mg SO₄/day/m², in general agreement with rates measured at other minesites.

The third task involved the creation and application of a predictive model, named MINEWALL, to the Main Zone Pit to determine if acidic conditions might develop during decommissioning. For reliable predictions, MINEWALL requires detailed input on water movement, pit design, fracture characteristics, acid generation/neutralization, and metal leaching. The best-fit simulation of the Main Zone Pit to current data indicated the water in the pit will always remain near neutral values, except during an initial flush of acidity as flooding begins.

The development of recommendations for further studies and for draft criteria of pit decommissioning completed this study. These recommendations highlighted the amount of detailed data required for reliable predictions and emphasized the primary role that pre-mining studies play in designing effective plans for decommissioning and closure. These recommendations were developed by Morwijk Enterprises Ltd. and do not necessarily reflect the views of Equity Silver Mines Ltd., the mining industry, or the provincial and federal regulatory agencies.



The Main Zone Pit, Equity Silver Mines Ltd.

Photograph taken in late September, 1989,
looking towards mine north.

1. INTRODUCTION

Mining operations consist of several primary and secondary components which are capable of affecting the quality of the surrounding environment. The primary components, which interact through exchanges of water and solids (Figure 1-1), often receive the most attention during environmental planning and monitoring. The first component, the mine or mined area, is the subsurface zone where ore is removed usually through an open pit or underground gallery. This mining activity leads to ore stockpiles and waste rock/spoils/overburden dumps which consist of disturbed, broken materials. If a mill is present, the processing usually involves additional disturbance and breaking of the ore, leaving a finer-grained waste deposit of tailings.

Each of the mine components has the potential for distinct, sometimes unique effects on the local flow and quality of groundwater and surface water. One potential effect common to all components is the development of acid drainage, which originates on broken surfaces exposed to air and water. This study specifically deals with acid drainage and associated metal leaching from mine walls.

Acid drainage from mine walls is typically viewed as less critical than acid drainage from tailings impoundments and waste-rock dumps for several reasons. Firstly, the size and exposed surface area of a mine is often significantly less than the size and surface area of the associated tailings impoundments and waste-rock dumps. Secondly, tailings and waste rock are usually piled on the land surface so that they are more visible. Thirdly, precipitation infiltrates through tailings and waste rock, resulting in seepage, whereas water tends to accumulate in a mine. Fourthly, because minewater must be collected and removed in order to enhance working conditions and wall stability during operation, handling of any acidic minewater is implicitly included. At the Rum Jungle Minesite in Australia, acid drainage from the open pits accounts for only 12% of total metal (copper) loading from the entire site and thus relatively little attention was paid to the pits (Northern Territory Department of Mines and Energy, 1986).

These reasons for the relative lack of emphasis on mine walls are essentially operational reasons, that is, there are other components during operation causing greater problems if acid generation is prominent and, whether acidic or neutral, inflowing minewater must be removed from the mine during operation. However, the impacts of mine walls can become more severe following the completion of mining.

Acid drainage from mine walls becomes more problematic during decommissioning when mine dewatering ceases, hydraulic equilibrium is established, and acidic minewater begins to flow from the mine to the local environment. For open pits, hydraulic equilibrium may involve flooding of part or all of a pit, resulting in a relatively large pool of acid water that migrates into local aquifers and surface watercourses. As an example, this problem is currently being faced by Anaconda Minerals Company at its Berkeley Pit in Montana, where the pit is currently flooding at a rate of approximately 43,900,000 liters a day and the pit water has a pH of 2.8-3.0 with a sulfate concentration around 7000 mg/L (Davis and Ashenberg, 1989). By the Year 2009, there will be more than 500,000,000,000 liters of

acidic water in the pit and this water will have begun to migrate into local aquifers.

For these reasons, the mining industry as well as federal and provincial regulatory agencies have commissioned this study of acid drainage from mine walls. Emphasis is placed on the Main Zone Pit belonging to Equity Silver Mines Ltd. near Houston, British Columbia. This pit has an unusually detailed database, which permits an investigation of the potential for acid drainage.

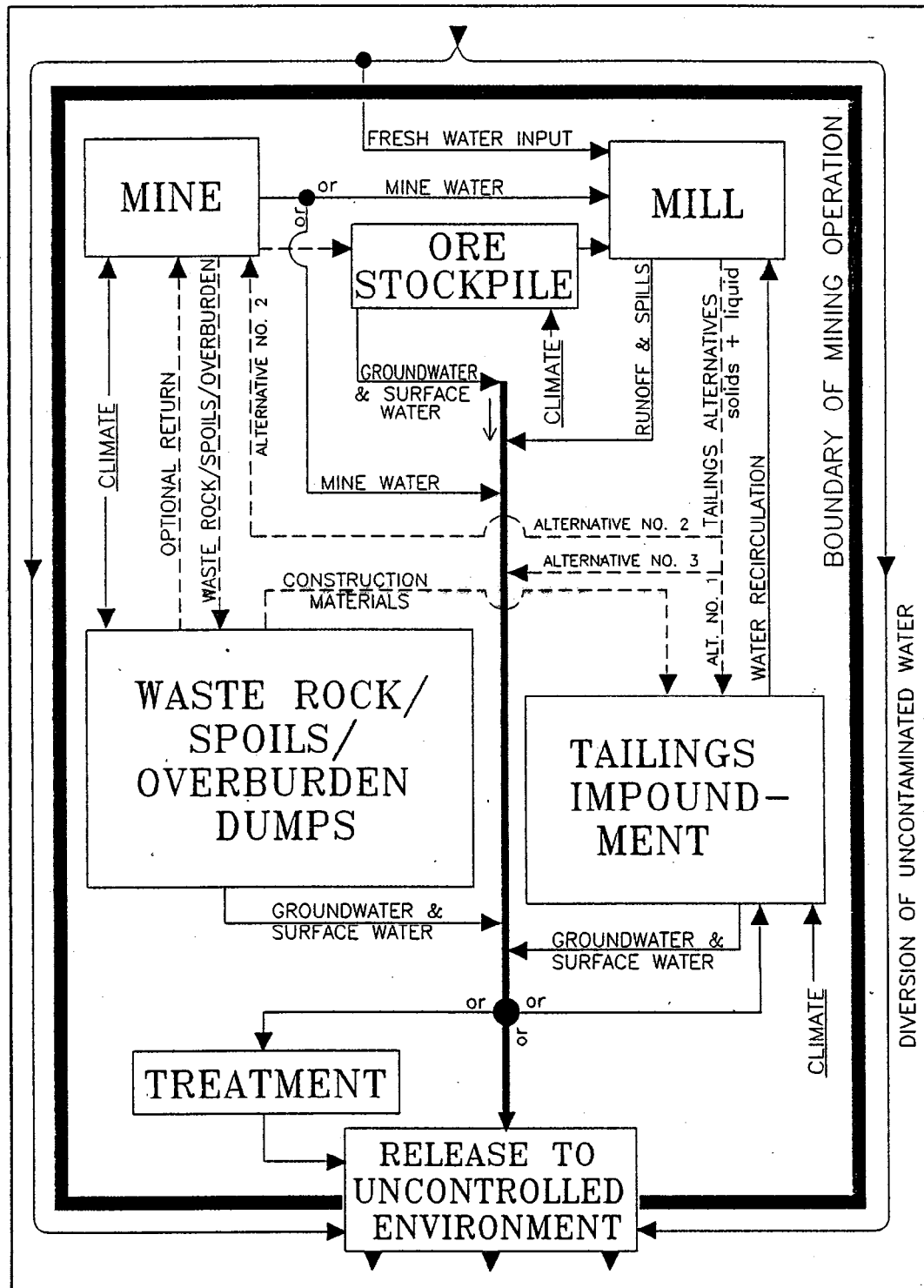


FIGURE 1-1. Schematic Diagram of the Water and Solids Balances of a Mining Operation. Solid lines represent water exchanges and dashed lines are exchanges of solids. (After Morin, 1988).

2. OBJECTIVES

The objectives of this study are to examine acid drainage from mine walls in four stages, focussing on open-pit walls. The first stage is a detailed literature review of acid generation and water movement in and near open pits with additional supporting literature from underground mines.

The second stage is a field study at Equity Silver Mines near Houston, British Columbia. At Equity, the Main Zone Pit is scheduled for decommissioning and the nearby Southern Tail Pit has already been decommissioned, filled with waste rock from the Main Zone Pit, and flooded. Due to the initially acidic conditions in the Southern Tail Pit, there is concern over the potential for acidic water to accumulate in the Main Zone.

The third stage is the development and application of a predictive model of acid drainage from mine walls during operation and after decommissioning. This model is based on the results of the field study at Equity and the literature review. As part of the terms of reference for this study, predictive simulations are limited to the Main Zone Pit.

The fourth and final stage is a series of recommendations for further studies and recommendations of draft criteria for the decommissioning of pits.

3. LITERATURE REVIEW

As part of this study on acid drainage from mine walls, a detailed literature review was undertaken to locate and critically assess existing literature. This review was conducted by remote searches of computerized databases, visual searches of the libraries at the University of British Columbia (UBC), and correspondence with researchers who have conducted studies on mine walls and acid drainage. The existing case studies, theoretical analyses, and modelling provided a foundation for the subsequent field studies at Equity Silver Mines.

The searches of computerized databases consisted of the selection of 8 primary keywords with an additional 5 keywords limiting the search to mining (Appendix A). These keywords were used in 22 databases of the Dialog system, 2 databases of the QL system, and one database on the Canole system. The searches emphasized both acid generation/neutralization and water flow, which is responsible for transporting acidity away from the sites of acid generation into the local environment.

Visual searches of the UBC libraries consisted of initial examinations of the Subject card catalog using the keywords of Appendix A, followed by an examination of shelves around targeted references. This approach led to the location of several important references not identified by the computerized search. Based on the references located by the searches, selected authors were contacted for details and any additional data and references.

3.1 Water Movement In and Near Open Pits

A key factor in understanding acid drainage from mine walls is the knowledge of water movement in and near the walls. From a simplistic viewpoint, acid drainage would not be such an environmental concern if products of sulfide oxidation remained at the oxidation sites. However, water often moves over the oxidation sites and dissolves the acid products, including acidity, hydronium (H^+) ions, and leached metals such as iron and zinc. This acidic water then flows into the local environment.

In order to appreciate the nature of water movement as reported in the literature, it is necessary to construct a conceptual model (Figure 3-1). In the model, water movement during active mining involves (1) precipitation, (2) runoff and surface flow, and (3) groundwater. Precipitation falls directly onto walls and benches, then flows downward into the underlying rock, becoming groundwater, or runs down the wall to the pit bottom. Runoff and surface water are usually controlled so that no major flows enter a pit, although surface water diversion cannot control the runoff originating directly around the crest of the pit. This water enters the pit then infiltrates into the benches, becoming groundwater, or runs down the wall to the pit bottom. Runoff and surface flows within a pit can be conceptually grouped as one basic "surface water" source.

Subsurface water, or groundwater, migrates in geologic strata that are either completely

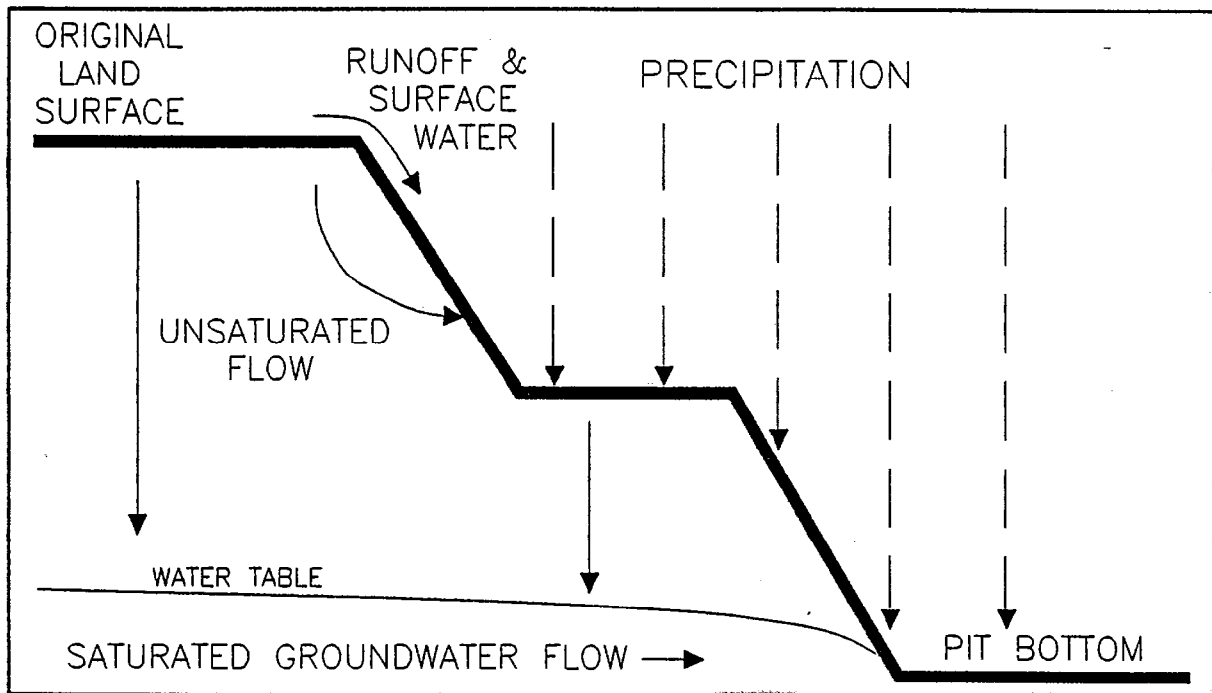


FIGURE 3-1. Schematic Diagram of Water Movement In and Near Pit Walls During Active Mining.

saturated with water or partially unsaturated. The physical laws governing water movement in these two groundwater regimes differ in complexity, but are generally similar. Movement of groundwater in the saturated zone is reflected in the elevation and slope of the water table. If the bottom of a pit is lower than the local water table and minewater is actively removed from the pit, the direction of groundwater flow in the saturated zone is predominately towards the pit (Figure 3-1).

In the unsaturated zone, groundwater originates in the surface-water sources discussed above and migrates downward to the water table or has a lateral component of flow towards the pit wall, contributing to water running down the wall (Figure 3-1). The lateral component of flow can be particularly enhanced in fractured metamorphic and igneous rock ("hard rock") in which lateral fractures may be oriented towards the wall and vertical flow of groundwater may be restricted. The importance of fractures will be discussed further in Sections 3.2 and 3.3.

Based on this analysis, the two basic sources of water near a pit wall are groundwater and surface water, and these two sources may be interactive depending on local hydrogeologic conditions. For walls in underground mines, surface water can often be dismissed from consideration. Case studies and theoretical analyses in the published literature will illustrate the nature and relative importance of these sources.

For groundwater, the most commonly reported information is dewatering of the saturated zone, leading to the development of a cone-like depression in the elevation of the

water table centered at the pit (e.g., Figure 3-2). This literature review has located 13

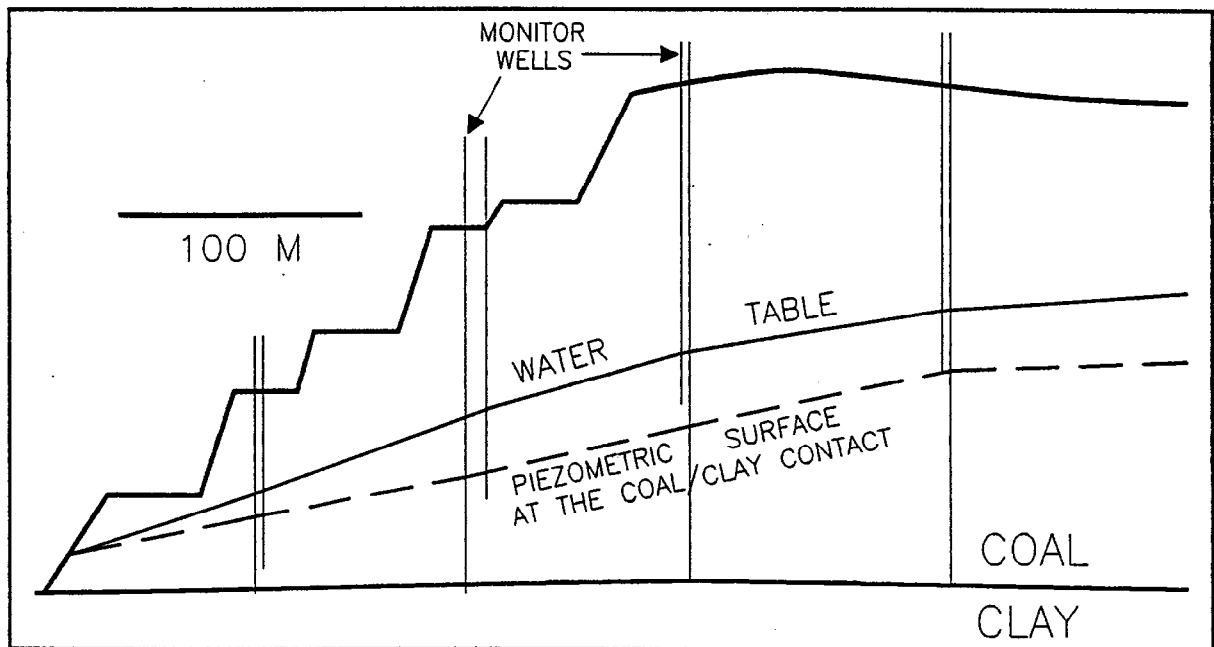


FIGURE 3-2. Example of Water-Table Drawdown Near An Active Pit: the Morwell Open Coal Pit, Australia. (After Fraser et al., 1982).

detailed case studies of water-table drawdown (Table 3-1), which demonstrate the site-specific importance of pit size, pit depth, hydraulic conductivity, and elapsed pumping time on the lateral extent of the drawdown and on the pumping rate needed to maintain a dry pit. Additional information in a few of these studies also highlights the importance of hydrogeologic boundaries, such as impermeable and permeable fault zones and nearby rivers, as well as recharge rates from infiltration, all of which are commonly referred to as "boundary conditions" in hydrogeologic studies. The unique combination of boundary conditions at a site determines the baseline characteristics of the local groundwater system and its response to mining activity. Kipp et al. (1983) reported unusual boundary conditions leading to a rare occurrence of a raised water table when a pit in the unsaturated zone increased recharge to the water table.

The case studies of Table 3-1 provide information on the regional hydrogeologic impacts of mining and are oriented, for the most part, towards groundwater control to improve geotechnical stability of pit walls. From the perspective of geotechnical stability, Brawner (1979) observed, "Procedures to control surface drainage are simple and well understood. Control of subsurface drainage has only recently been recognized on many projects as a serious and potentially costly problem". The studies of Table 3-1 focus on subsurface drainage and the dewatering of the saturated zone near the pit. The limitations of these case studies from the perspective of this literature review are (1) unsaturated flow is not examined, but its importance is alluded to in a few studies where recharge rates to the water table are reported, (2) the studies do not consider any geochemical effects such

as exposing more rock to oxygen (Section 3.2), and (3) the studies provide little information of small-scale water movement at the pit walls, which is critical in the flushing of acid products from the walls and nearby unsaturated fractures. In fact, no information on small-scale water movement adjacent to pit walls could be located in the literature, although such information does exist for a few underground mines (Section 3.3).

The case studies located by this review provide a general indication of potential levels of inflows to pits, which would require treatment if the water passes over sulfide-oxidation sites or mixes with acidic drainage. Also, the case studies permit the calculation of the volume of recently-drained rock and sediment which may generate acidity based on the depth and lateral extent of drawdown.

No detailed case studies of surface-water sources near pit walls could be located. However, because groundwater near a pit is at least partially derived from surface water and because surface flows into a pit can result in flooding, it is well known that the control and diversion of surface water is critical. The relative lack of published case studies may simply reflect the perceived simplicity and widespread knowledge in management of surface water relative to groundwater. The remainder of this literature review focusses on groundwater.

Following active mining, pit dewatering ceases and the pit may begin to fill with water if it extends below the original water table. The conceptual model for water movement during decommissioning (Figure 3-3) includes the same sources of surface water and groundwater as during operation (Figure 3-1). However, a critical issue becomes the extent to which the pit will fill with water. The precise level will depend on the site-specific balances of surface-water and groundwater sources, pre-mining conditions, hydrogeologic characteristics, and hydrogeologic boundary conditions. As a simplistic analysis, pits excavated in relatively flat terrain could generally be expected to fill to a level near the pre-mining water table (Diagram A, Figure 3-3), if the site is returned to pre-mining conditions. This dependency of reliable predictions and planning on pre-mining conditions provides additional impetus for detailed pre-mining hydrogeologic studies.

Regulatory recognition of this dependency is evolving (Evans and Hailu, 1984).

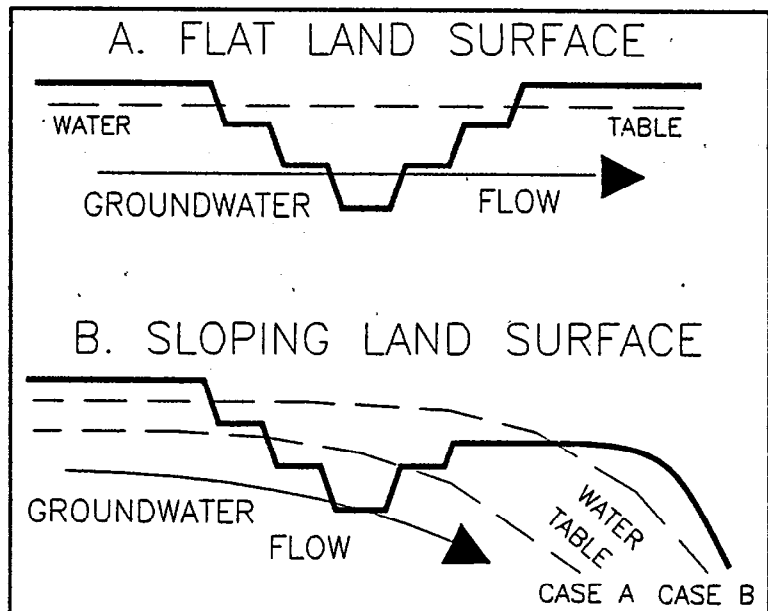


FIGURE 3-3. Schematic Diagram of Water Movement In and Near Pit Walls After Mining.

TABLE 3-1
Case Studies of Groundwater Flow to Pits

<u>Location and Type of Mining</u>	<u>--Approx Area (m²)</u>	<u>Pit-- Depth (m)</u>	<u>Max Draw-down (m)</u>	<u>Lateral Extent of Drawdown (m)</u>	<u>Elapsed Time</u>	<u>Pumping Rate (m³/d)</u>	<u>Reference and Miscellaneous</u>
Faro Mine, Yukon, base metal & Ag	840,000	90-150	10	-	1-2 wks	2180	Lopaschuk, 1979; 380 m ³ /d from lateral drains, 1800 as inflow to pit
Whitewood, Alberta, coal	110,000	20-40	20	1200	>6 yrs	410-685	Sumer et al., 1987; recharge = 5% of 50 cm/yr; dewater wells; model $K=10^{-6}$ - 5×10^{-4} m/s, $S_y=0.05$, $S=0.001$
Twin Buttes, Arizona, base metal?	1,170,000	230	90	300	1.3 yr	gen <5	Pentz, 1979; underground galleries with lateral drill holes for dewatering; $K=10^{-8}$
Shirley Basin, Wyoming, uranium	150,000	90	21	>300	1 yr	>1440	Straskraba & Kissinger, 1982; dewater wells/lateral drains $K=2 \times 10^{-5}$ m/s, $S=0.00054$
Southern Illinois, coal	-	-	>24	>300	-	-	Oertel & Hood, 1983; $K < 10^{-7}$ m/s
Kentucky, coal	-	-	10 & <u>increase of 1.5</u>	-	<1 month	-	Kipp et al., 1983; pits opened in unsaturated zones above wells with + and - effects on recharge
Edinburgh, Scotland:							
-Haywood Pit, coal,	225,000	71	45	-	-	26,000	Norton, 1982; dewater wells

-Blindwells Pit, coal	1,200,000	60	30	<1000	2 yrs	35,000- 69,000	Norton, 1982; area contains abandoned, flooded undergr. mines; water table stable prior to pit mining; dewatering wells
Piaski, Poland, coal	-	124	>100	8000	-	560,000	Seweryn, 1982; dewater wells
Nyirad, Hungary, bauxite	2 pits: 5,000,000 2,500,000	>100 >100	100	45000	21 yrs	430,000	Bocker and Vizy, 1982; Paris, Karst limestone; $K=10^{-5}$ - 10^{-4} m/s, poros=2-4%; $S=0.00002$; dewatering wells; recharge= 25% of 63 cm/yr
Queensland, Australia, limestone	10,000	27	25	>2000	7 yrs	1,400	Dudgeon, 1987
Victoria, Australia, coal	3,000,000	-	130	50000	22 yrs	68,000	Evans, 1987; aquif $K=6 \times 10^{-6}$ - 2×10^{-4} m/s, $S=0.00002$ - 0.0003 ; K of aquitard= 10^{-11} m/s
South Australia, coal, trial pit	200,000	60	40	-	1 yr	17,300	Armstrong, 1982; aquifer $K =$ $6-9 \times 10^{-5}$ m/s; aquitard $K =$ 10^{-8} ; series of emergency wells for water control
Neyveli, India coal	7,770,000	70	49	11000	18 yrs	160,000- 320,000	Hofedank, 1979; Brealey, 1965; Transmissivity= $0.01 \text{ m}^2/\text{s}$; dewatering wells

Situations could also arise where the post-mining water table could be higher than the pre-mining level. A post-mining enhancement of infiltration to the water table, which could be caused by nearby waste-rock piles or tailings impoundments with elevated water tables, could result in such a development. In any case, several years or decades may be required before an equilibrium level is achieved, although generalized modelling suggests up to thousands of years could be necessary (Crowe and Schwartz, 1984).

In sloping terrain, the ultimate equilibrium level will depend on the relationship of the pit to the slope. Where the pre-mining water table intersected the pit walls on all sides (Diagram B, Case A, Figure 3-3), it may be reasonable to expect only the lower portion of the pit to flood. If the pre-mining water table was higher than the lower portion of the pit wall (Diagram B, Case B), the equilibrium water level may completely submerge the lower side of the wall and a dam over the lower wall may result in additional portions of the higher wall being covered.

Water filling the pit towards its equilibrium level will be drawn from surface-water sources and groundwater. If surface water is the dominant source, the rate of water-level rise will likely vary with climatic conditions. If groundwater is the major contributor, the rate will decrease through time as the hydraulic gradient into the pit decreases. At equilibrium, the pit will become an integrated part of the groundwater flow system with groundwater and surface water entering one portion of the pit perimeter, flowing through the pit, then exiting through the opposite perimeter. This behavior will be perturbed to some degree by the differing response of the water table and the pit level to climatic events.

One complication in pit flooding can arise whenever the pit is backfilled with waste rock or tailings. If a pit were backfilled with coarse-grained material, the preceding conceptual model of pit decommissioning would be expected to remain applicable. However, fine-grained backfill such as tailings could result in a water table mound developing in the backfill above the surrounding water table. In such cases, the backfill would act as a local recharge area, contributing groundwater to the subsurface, rather than allowing groundwater to simply pass through the backfill.

With the conceptual decommissioning model developed to this point, it is now appropriate to examine published case studies of flooded pits, which were found to be few in number. A detailed study of the base-metal Berkeley Pit in Montana (Davis and Ashenberg, 1989), reportedly the second largest pit in the U.S.A., began filling in late 1983 and the water level is predicted to flow over the pit crest around Year 2009. This suggests the conceptual Case B (Diagram B, Figure 3-3) applies here, but the limited data in the publication do not seem to support Case B. Furthermore, the geologic contact between rock and overlying sediments will be submerged by 1996. Unless the original water table was far above this contact, an equilibrium level may be reached before Year 2000 and below the pit crest, as the water flows out of the pit through the sediments.

By October, 1987, the lower 340 meters of the Berkeley Pit had been flooded and the water level was rising at a rate of 22 meters a year. This rate was attributed to undifferentiated inflows of groundwater and surface water from several site-specific sources,

totalling 28,700,000 liters a day including an estimated loss to evaporation of 300,000 liters a day. This is not sufficient detail on water movement to properly analyze and assess this site through the conceptual models developed in this section, suggesting some uncertainty may be inherent in the published predictions.

As previously mentioned, elevated groundwater levels around a pit contribute to wall instability and this is true of the Berkeley Pit. Depth sounding indicated that 38 meters of the pit bottom had been filled in to a flat surface by wall sloughing.

The second detailed case study of pit flooding was at the Rum Jungle uranium mine in Australia (Goodman et al., 1981; Northern Territory Department of Mines and Energy, 1986). Two pits, Whites and Intermediate, were examined in greatest detail. Most of the studies concentrated on water chemistry and acid drainage (Section 3.2) and little emphasis was placed on water movement, particularly groundwater. This resulted in difficulty and ambiguity in interpretations of water chemistry and contaminant transport. Whites Pit, with an area of 10.5 hectares, a depth of around 50 meters, and a storage capacity of 2,700,000 m³, flooded to equilibrium in a year with the assistance of a diversion of river water. The yearly flow of water through the flooded pit is around 19,000,000 m³, which does not including reportedly significant groundwater flow through intercepted aquifers. The Intermediate Pit, with an area of 4 hectares, a depth of around 78 meters, and a storage capacity of approximately 1,100,000 m³, also flooded in a year. The yearly flow of [surface] water through the flooded pit is around 18,000,000 m³.

Additional case studies of flooded pits include the Southern Tail Pit at Equity Silver Mines (Section 4.2), the Rabbit Lake Pit in Saskatchewan in which tailings are being placed and the rise in the water level is being actively controlled by pumping, and the Midnite Mine in the State of Washington. Based on a photograph, the flooded Midnite Pit appears to be relatively small and lies in sloping terrain so that a significant area of wall is exposed at one end of the pit. A detailed report on this pit is currently in internal review by the U.S. Geological Survey and is not available for public inspection.

The preceding discussion on the operational and decommissioning phases of pits have highlighted the need for detailed site information and for computer modelling (see also Section 6). The following text is a brief discussion on relevant aspects of modelling. The existing general types of groundwater models based on finite difference and finite elements are generally suitable for site-specific simulations of pit surroundings. However, experience has shown that generally acceptable, but not highly accurate, simulations are frequently obtained (such as in a few case studies in Table 3-1 and Unland and Hall, 1980, for Key Lake, Saskatchewan). The lack of detailed accuracy in these simulations can usually be attributed to the complexity of groundwater systems on a regional scale as well as the unpredictable effects of mining such as (1) the effects on groundwater movement and fracture/aquifer interconnections caused by exploration boreholes (Brealey, 1965), exploration trenches (Williams et al., 1979), and nearby oil and gas wells (Emrich and Merritt, 1969) and (2) the development of a highly conductive "skin" of rock around the pit (Evans, 1987). For underground mines, the formation of a conductive skin appears to be more restricted in lateral extent (Pusch, 1989; Toran and Bradbury, 1988) unless subsidence occurs.

Analytical models are also available to simulate pit inflow, but these exact solutions are based on ideal conditions that do not apply to most groundwater regimes near pits. Nevertheless, these models can provide a gross estimation of groundwater behavior if required at early stages. A relatively flexible suite of analytical solutions are provided by McWhorter (1981).

3.2 Acid Drainage and Metal Leaching in Open Pits

Within the framework of water movement developed in Section 3.1, the results of the literature review on acid drainage and metal leaching from pit walls will be presented here. This section will address both the operational and decommissioning phases of pit mines.

As in Section 3.1, a conceptual model for acid drainage from pit walls will be developed to aid in the presentation of the literature review. Acid drainage and accelerated metal leaching are consequences of oxidation of sulfide minerals, elemental sulfur, and some organic forms of sulfur, which creates an acidic environment around the sulfur-bearing particle. Water movement over the oxidation site mobilizes the acidity, sulfate, and leached metals. If this water then encounters neutralizing minerals or mixes with strongly alkaline water, the acidity will be neutralized and dissolved metals may chemically precipitate to a significant extent. This on-going competition between acid generation and acid neutralization is not always recognized. It is the delicate balance between acid-generating and acid-neutralizing reactions that determines the extent and severity of acid drainage and the potential for the lag time between initially neutral drainage and subsequent acid drainage. In situations where neutralization is dominant, the reliable indicator of the extent of acid generation that occurred prior to neutralization is usually sulfate (e.g., McCurry and Rauch, 1986; Helz et al., 1987), although geochemical limitations such as gypsum solubility could render sulfate less reliable.

Acid generation can occur on the surface, or outer boundaries, of grains and fracture planes as well as within a grain or block of rock. Based on this conceptualization, there are two localities of acid generation: surficial and internal relative to the smallest divisible grain or block at a site (Figure 3-4). Surficial generation is a function of the exposed surface area of a block of rock whereas internal generation is a function of the exposed surface area, distance to the center of the grain, and the volume of the grain.

In typical metamorphic and igneous ("hard-rock") terrains such as found at many metal mines in British Columbia, the smallest independent block is usually defined by fractures and joints. As a result, surficial acid generation is synonymous with acid generation on fracture surfaces and internal acid generation refers to any generation within blocks of rock which could have dimensions of centimeters to meters. Internal acid generation in hard rock is often considered negligible relative to surficial generation as a consequence of typically low permeability of the block to water and air.

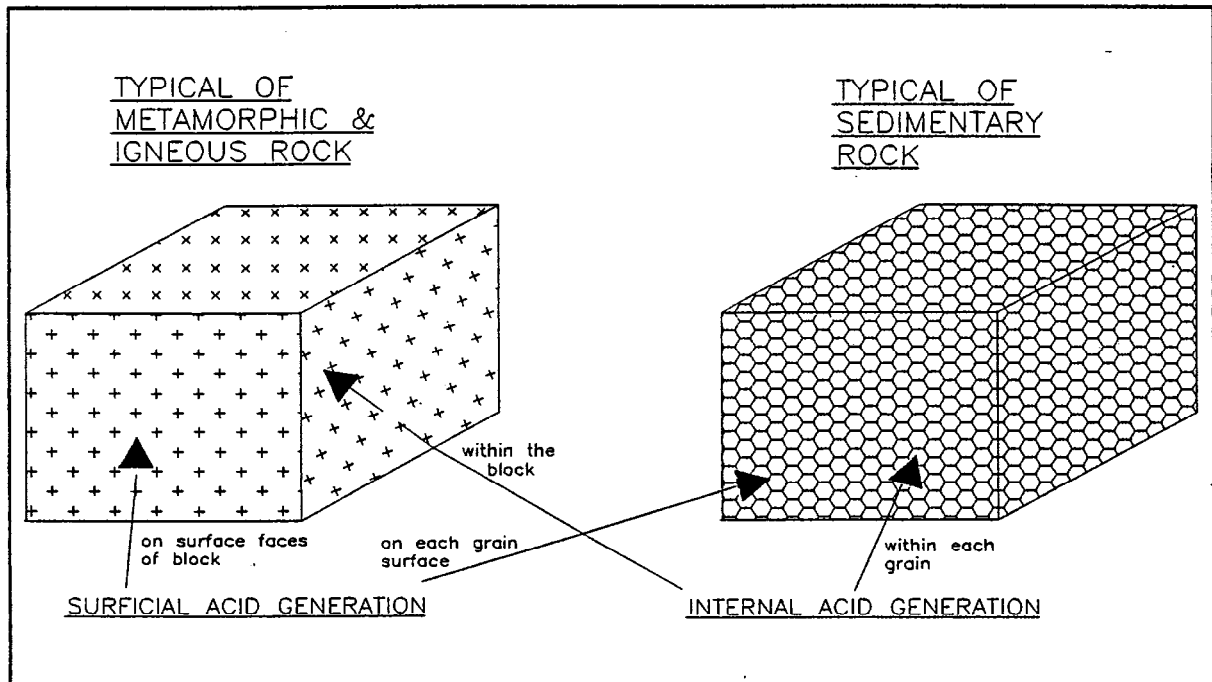


FIGURE 3-4. Schematic Diagram of Acid Generation in Metamorphic/Igneous and Sedimentary Rock.

In sedimentary terrains, the sediment or rock may consist of sand-, silt-, or clay-sized grains. In these cases, internal and surficial acid generation could be significant due to the size, number and permeability of grains and the exposed surface area of the grains. Research at the Ohio State University (Section 3.3) showed that surficial and internal acid generation within porous grains, rather than fracture blocks, were the primary sources of acidity in a coal mine (Morth et al., 1972).

Indurated (cemented) sedimentary materials result in a complex combination of the hard-rock and sedimentary scenarios. This is the result of the combined presence of the grains, the cementitious material that seals the surfaces of some or all grains, and the resulting fracture surfaces exposing portions of numerous indurated grains.

Based on Figure 3-1, there is theoretically a flow of groundwater only into a pit during operation because all hydraulic gradients are towards the focus of the water-table drawdown. For this reason, acid drainage from pit walls should not affect local groundwater quality during operation. However, it is possible, primarily in regions with steeply sloping pre-mining water tables, for groundwater to flow into one side of the pit, drain to the pit bottom, infiltrate into the underlying rock, and continue flowing downgradient. In fact, the documented cases of acid drainage migrating from active pit walls are drawn from the eastern U.S. coal fields where coal is locally mined by surface excavations into sloping valley walls. The chemical analyses confirm the migration of wall-derived acid drainage into local groundwater systems during operation, but this is probably

not the typical scenario that would be found at most pit mines in British Columbia.

In contrast to case studies on water movement (Section 3.1) which were predominately performed at operating pits, most case studies on acid drainage from pits were performed at abandoned mines. This is a consequence of the environmental impacts when dewatering is terminated and the pit becomes an integral part of the local environment.

McCurry and Rauch (1986) and O'Steen and Rauch (1983) evaluated groundwater impacts of mining in West Virginia based on samples from over 100 wells, springs, and streams near open-pit and underground mines. The researchers do not specifically state whether the pits were active or flooded, but the introductory remarks suggest mining is ongoing. Based on the assumption that local sulfate concentrations greater than 50 mg/L represent mining impacts, pit mines were found to contaminate groundwater systems with a sulfate concentration of approximately 2000 mg/L to lateral and vertical distances of 460 and 30 meters, respectively. Concentrations were found to decrease exponentially with distance from the mines. Surprisingly, upslope as well as downgradient wells were found to be impacted (O'Steen and Rauch, 1983), which would violate hydrogeological principles but is not explained by the authors. The distances of impacts were found to be greater for pits than for underground mines, which was attributed to the locations of pits in recharge areas [near valley crests] and the generally higher hydraulic conductivity of near-surface strata.

Based on the groundwater database of Rauch and colleagues, groundwater impacts were found to occur in three stages: (1) initial impacts were minor due to the months-long lag in acid development in the pit and the length of time for groundwater to travel to adjacent wells, (2) a rapid increase in contamination then occurred, persisting for 2-5 years, with peak concentrations reached 4-6 years after initiation of mining, and (3) a phase of declining concentrations took place over 20-30 years in pit mines and over 40 years in underground mines.

In another study, Ahmad (1974) reported the water chemistry draining from the Sheban Strip Mine in Ohio as:

pH	SO ₄	Acidity	Fe	Al	Zn	Ni	Cu	Cd	Ca	Mg
3	2167mg/L	323	142	100	2.6	2.5	0.08	0.025	520	550 mg/L

The low value of acidity relative to sulfate and the elevated concentrations of calcium and magnesium probably indicates some neutralization of acidity has occurred, but is insufficient to regulate water chemistry. There is some ambiguity in this reference in that the active or abandoned state of the pit is not discussed and in that the above water chemistry may include impacts of spoil piles. Nevertheless, the sulfate concentration of 2167 mg/L is in agreement with the value of about 2000 mg/L noted by McCurry and Rauch (1983), which is likely the limit of gypsum solubility for these waters.

Jackson (1982) reported water chemistry of open-pit leachate in the southern Rocky Mountains of Alberta and British Columbia. Although not specified by the author, the pits may be partially or fully flooded because the mines are said to be "orphaned". In the leachate, sulfate is approximately 60 mg/L whereas total alkalinity is around 200 mg/L and

calcium plus magnesium is near 70 mg/L. The excess alkalinity suggests neutralization is regulating water chemistry and pH, although no pH value is reported.

Emrich and Merritt (1969) noted that minewater in acid-generating underground mines in the eastern U.S. was initially alkaline then became acidic. Further to the west of this area, limestone beds were found to be associated with coal strata so that pH remained neutral (demonstrated by Parkhurst, 1987), but concentrations of sulfate still increased. These researchers found that discharges directly from coal mines had a strongly acidic pH and relatively heavy sulfate concentrations. Conversely, nearby groundwater was less acidic with lower sulfate concentrations than the discharges, probably due to neutralization and dilution in the groundwater systems. However, this nearby groundwater was distinctly more acidic than the more distant, non-mining-related groundwater in the same systems.

Downs and Stock (1977) summarized several case studies of acid drainage from mines (Table 3-2), although it is not clear whether these are pits or underground workings nor whether spoils and waste rock are involved. The pH values are in the range of 2.3-3.4, similar to the value reported above by Ahmad (1974) and by other researchers (e.g., Emrich and Merritt, 1969, for underground mines). Sulfate values are in the range of 800-2800 mg/L, similar to other studies and likely reflecting gypsum solubility. Where ferrous and ferric iron are reported in Table 3-2, the ratios are within an order of magnitude of 1.0, reflecting redox buffering by the $\text{Fe}^{2+}/\text{Fe}^{3+}$ redox couple at acidic pH (Morth et al., 1972).

TABLE 3-2
Analyses of Acid Drainage from Mines (Down and Stocks, 1977)
(concentrations in mg/L)

	Coal Mine, Lancashire	Coal Mine, Pennsylvania	Coal Mine, USA	Uranium Mine, Ontario	Iron Mine, Ontario
pH	3.2	3.4	3.0	2.3	2.6
Acidity	647	230	1560	3180	1600
SO [sic]	-	800	-	2800	2280
Fe^{2+}	2305	68	445	-	-
Fe^{3+}	238	12	208	-	-
Total Fe	-	-	-	280	960
COD	338	-	-	50	30
Tot Solids	20220	-	4110	6170	4180
TSS	trace	-	-	15	355

In a well defined case of pit flooding, Davis and Ashenberg (1989) reported on the Berkeley Pit in Montana. The pit was filling with water derived from groundwater and surface flows. The pit water had a pH around 3, which was attributed to bacterially mediated pyrite oxidation in the hydraulically connected underground workings and shafts and to surface inflow from acidic leach pads. Concentrations with depth (Table 3-3) demonstrated the presence of some chemical stratification in the pit water. However, the

lower pH near the surface was attributed to inflow of the leach-pad water rather than oxidation of iron and precipitation of ferric oxyhydroxides. Davis and Ashenberg found that the trends of increasing total and ferrous iron and decreasing values of Eh with depth reflected the increasingly reducing conditions with distance from the atmosphere. Metal leaching associated with the acid drainage was significant with cadmium concentrations reaching 1.9 mg/L, copper reaching 214 mg/L, zinc reaching 500 mg/L, and manganese reaching 165 mg/L. Notably, lead was less than 1 mg/L due to the general lack of exposed galena (PbS) in the area.

TABLE 3-3
Water Chemistry in the Flooding Berkeley Pit, Montana
(from Davis and Ashenberg, 1989; concentrations in mg/L)

<u>Depth (m)</u>	<u>pH</u>	<u>Eh(V)</u>	<u>Fe²⁺</u>	<u>Fe³⁺</u>	<u>Total Fe</u>
0	2.76	0.82	0.25	196	196
1	2.72	0.72	60	142	202
3	2.84	0.64	262	14	276
15	2.95	0.57	622	28	650
31	3.08	0.50	900	10	910
66	3.15	0.46	938	-	854
100	3.15	0.47	944	14	958
130	3.14	0.46	962	24	986

Visual seasonal changes and variable measured chemistry in the Berkeley Pit suggested that significant variations in the upper few meters of pit water occurred throughout the year, including a predominant reduction of ferric iron to ferrous under ice cover with re-oxidation during summer months. Variations in water chemistry to a depth of about 30 meters were less significant, and below 30 meters chemistry was generally constant. Speciation and solubility calculations with various computer programs indicated the following minerals played a major role in regulating water chemistry within the pit: ferric hydroxide, gypsum, jurbanite (AlOHSO_4), and potassium jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$). Simulated additions of a strongly alkaline solution ($\text{pH}=11.3$ and total alkalinity=271 mg/L) resulted in essentially no change in aqueous pH in one unit of pit water until more than two units of the alkaline water were added then pH increased rapidly to 5-7 then generally stabilized after more than four alkaline units were added. This can be explained by mineral dissolution and precipitation (e.g., Morin, 1988). The requirement of more than four units of strongly alkaline water for each unit of pit water highlights the strongly acidic nature of the pit water and the need for early addition of neutralizing water so that sufficient volume exists to hold all water until mixing is accomplished.

In another detailed study of flooded pits, the water chemistry and microbiology were examined at two flooded pits at the Rum Jungle Mine in Australia (Goodman et al., 1981; Water Resources Division, 1986; Northern Territory Department of Mines and Energy,

1986; Henkel and Alcock, 1986 and 1987). The Whites Open Cut (pit) flooded within one year after termination of mining and had a pH of 4.75 and sulfate of 180 mg/L. However, unneutralized tailings and treatment raffinate were dumped into this pit through the 1960's so that by 1974 pH had decreased to 2.4 with sulfate at 9000 mg/L. The Intermediate Open Cut also flooded within one year and in 1974 had a pH of 3.5 with sulfate at 2000 mg/L. The microbiological study of these two pits (Goodman et al.) identified the presence of Thiobacillus ferrooxidans, sulfate-reducing Desulfovibrio sp., and a single-cell algae of the Chlorella genus. Additionally, T. denitrificans which oxidizes sulfide using nitrate was identified in the Intermediate Pit. The authors stated that at least some of the bacteria and all of the algae were probably washed into the pit. However, their conclusion that significant underwater acid generation must be occurring, despite low oxygen concentrations, because Thiobacillus was found in the acidic pit water is questionable. Later reports stressed the uncertainty by suggesting that some or all of the acidic pit water originated as groundwater inflow from nearby acid-generating rock dumps and from the aquifer between the pits. This would appear to be a more likely explanation, especially in light of detailed research in the U.S. (Section 3.3).

Whites Pit was found to have chemoclines and thermoclines within the upper 15 meters of water. For this reason, the treatment procedure involved pumping the deeper, more dense acidic water into a treatment plant and then returning the less dense, treated water to the top of the pit water. After some practical problems, including shallow mixing of treated and acidic water, a shallow pH-neutral layer was established with the assistance of in-situ application of lime. Treatment then proceeded until most of the pit water had been treated and a thick layer of neutral-pH water was formed over the remaining untreated water. Values of pH and sulfate during this procedure were 2.7 and 7800 mg/L, respectively, prior to treatment, 7.3 and 2700 mg/L just after treatment, and 6.0 and 200 mg/L after stabilization of the chemistry. Through the annual wet and dry seasons, water chemistry improved when there were inflows of neutral-pH surface water and worsened when evaporation and groundwater inflow were dominant.

The Intermediate Pit at the Rum Jungle Mine was found to not have significant chemoclines and thermoclines so that the treatment procedure used with Whites Pit was not feasible. Instead, hydrated lime was applied directly to the pit and the settled sludge was removed. Values of pH and sulfate during this procedure were 3.5 and 3100 mg/L, respectively, prior to treatment, 9.5 and 3250 mg/L just after treatment, and 5.9 and 200 mg/L after stabilization of water chemistry. Like the Whites Pit, water chemistry improved when there were inflows of neutral-pH surface water and worsened when evaporation and groundwater inflow were dominant.

Despite an original budget of \$16,000,000 for rehabilitation of the Rum Jungle Mine, apparently little attention was initially paid to the groundwater system. As interpretations of water chemistry in the pits and other mine components began after rehabilitation, unexpected problems arose such as a general trend of decreasing pH and increasing metal levels in the pits. These problems were suspected to be groundwater-related because most of the groundwater was believed to be highly acidic. The slow movement of groundwater through the area and into nearby waterbodies led to the speculation that problems with water chemistry and metal loadings would continue for some time, despite the extensive

surficial rehabilitation, until the acidity and mobile metals were flushed from the subsurface (Northern Territory Department of Mines and Energy, 1986).

3.3 Research by the Ohio State University

Through the decade of the 1960's and the early 1970's, numerous Masters and Ph.D. theses were completed in the Department of Geology at the Ohio State University on various aspects of acid drainage. The results of the theses and of related research contracts provide the only integrated study of acid drainage from mine walls (Morth et al., 1972), including both water movement and acid generation, that could be located by this literature review. For this reason, the results warrant this separate subsection.

Morth et al. (1972) explained that control of acid drainage from underground workings through mine sealing and laboratory studies was conducted in the 1920's in West Virginia. Through the 1960's, research at the Ohio State University quantitatively demonstrated many conclusions that are commonly accepted today. These conclusions include:

- o "sulfur ball" pyrite (now referred to as framboidal pyrite) had a greater surface area and reactivity than crystalline pyrite (1963),
- o the rate of pyrite oxidation was dependent on O_2 concentration (1964),
- o water is both a reactant and a reaction medium (1965),
- o 100% humidity results in the same oxidation rate as liquid moisture (1965), and
- o nitrogen gas can slow the rate of pyrite oxidation by competing with oxygen for "reaction sites" (1966).

Later research indicated that the often-quoted study by Singer and Stumm (1969) was:

- o incorrect in stating that ferric iron could not exist in contact with pyrite,
- o incorrect in stating that the overall rate of pyrite dissolution was independent of the surface structure, and
- o incorrect in stating that the controlling reaction in overall pyrite oxidation is the oxidation of ferrous iron.

Additional research indicated that overall pyrite oxidation was determined by two independent oxidation reactions that proceed at variable, site-specific rates. These reactions are direct oxidation by O_2 , which is determined by the O_2 concentration below 2% and is independent of the O_2 concentration above 2%, and oxidation by ferric iron, which is

determined by the ratio of free Fe^{3+} to free Fe^{2+} and is inhibited by ferrous iron. Microbiological research indicated that Ferrobacillus ferrooxidans accelerated the oxidation rate by a factor of 10-50, but only after 70-80% of the aqueous iron was in the ferric state. Field monitoring documented "flushouts" of accumulated acidity by storms, which increased concentrations of sulfate, acidity, iron, and hardness by 30-1000%. Mass balance calculations indicated sulfate was the indicator of total acid generation, which was numerically equal to the sum of acidity plus hardness, where hardness represented any neutralization.

Based on this research, there were 5 conditions believed to be common to all pyritic systems (Morth et al., 1972):

1. the environment at the reaction site determines the reaction rate,
2. oxygen transport predominately occurs in the gas phase,
3. water vapor with 100% humidity produces a similar rate of oxidation as liquid moisture,
4. the removal (flushing) of oxidation products away from the reaction site has no effect on the oxidation rate, and
5. the reaction does not occur on the bulk [fracture] surface, but on pyrite embedded in the porous structure [presumably, on and within the individual grains, see right-hand side of Figure 3-4].

In order to conduct field studies of acid drainage, the Ohio State University established the McDaniels Research Complex at the McDaniels Mine in southeastern Ohio. This mine was a small test drift (underground) mine extending 12-14 meters into a hillside. Flowrates and chemistry were measured for years, the mine was sealed, and the effect of varying gasses within the mine was tested. Variations in O_2 within the mine were predicted to cause variations in chemistry within 1-2 months based on flushing rates, but variations actually occurred after 6-8 months suggesting acid generation occurred predominately outside of flushed areas. Cores collected behind the coal faces in the mine indicated oxidation was occurring up to a distance of 15 meters. Six large-diameter auger holes into the coal seam on the opposite side of the hill demonstrated that initially alkaline groundwater became acidic with time.

From Auger Hole 3, 1 cm^3 blocks of coal and shale were experimentally monitored for oxygen uptake. Results were:

	<u>coal</u>	<u>shale</u>
O_2 uptake ($\mu\text{g/hr/cm}^3$)	1	3
After Cl_2 exposure to kill bacteria	0.7	3

The difference in the rates between shale and coal was reportedly attributed to the higher pyrite content and porosity of the shale. For the purposes of this study, the uptake rates

can be converted on the basis of the surface area of the blocks (i.e., assuming impermeable blocks) to obtain 40 and 120 mg O_2 /day/ m^2 for coal and shale, respectively. These rates are equivalent to sulfate productions of 70 and 205 mg SO_4 /day/ m^2 . A comparison of sulfate production in strongly acid-generating impermeable blocks in British Columbia (17 mg SO_4 /day/ m^2 , Cinola Gold Project) suggests the permeability of the block (Figure 3-4) enhances the bulk rate of acid production normalized to block surface area by over one order of magnitude.

Within the McDaniels Mine, blocks of coal were isolated from adjacent coal, but left in place, by cutting channels 15-30 cm deep around the blocks and filling them with polyurethane foam. Faces of the blocks were washed every 4-8 weeks and rates of acid production were found to range from 20-750 mg acidity/day/ m^2 , in agreement with the aforementioned oxygen uptake corresponding to 70 and 205 mg SO_4 /day/ m^2 . These lower values are generally comparable to the rates measured at Equity Silver Mines (Section 4.1.2).

Two blocks of coal with dimensions of 1x2x4 inches were placed in sealed humid cells with excess water placed in the bottom of the cells out of contact with the coal. The cells were occasionally opened to maintain oxygen levels. Condensation formed on the blocks and dripped into the excess water. Water analyses indicated the following production rates (adjusted here to surface area of block):

	---- mg / day / m^2 ----		
	<u>acidity</u>	<u>sulfate</u>	<u>iron</u>
Batch 1 (196 days)	8.0	1.3	1.8
Batch 3 (72 days)	3.0	2.3	7.3
Cinola rock, B.C		17	

The cause for lower observed rates in this test may have simply been the lack of flushing to remove all accumulated products on and within the blocks.

Morth et al. (1972) developed equations to simulate and predict oxygen movement into a pore channel. The equations included changes in atmospheric pressure which could drive fresh oxygen into a pore channel through compression of air within the channel. To standardize the model to actual conditions, 1 gram of concentrated pyritic material at a size of 60 mesh was found to consume 25 ug O_2 /hour/gram at 25°C.

With relevant issues of acid generation accounted for, Morth et al. (1972) addressed water movement. Based on studies at the McDaniel Mine, three primary mechanisms of water movement were identified:

1. unsaturated flushing of surfaces by trickling water,
2. saturated flushing of channels by inundation of the channel, temporarily halting oxidation, and
3. migration of acidic condensation originating from the moist atmosphere and hygroscopic

In order to determine the acid loadings attributable to each of the three mechanisms of water movement, simulations were performed for the McDaniels Mine, the Decker Mine with an acid output of 76,000 kg/year (1964), and the aforementioned Auger Holes 1, 3, 4, 5, and 6 near the McDaniels Mine. The best-match results of acidity loadings and flow dependencies, based on an approximated water table to define inundation and normalized to surface area based on the area "providing water", are summarized in Table 3-4.

	<u>McDaniels</u>	<u> ---- A U G E R H O L E ---- </u>					<u>No. 6</u>	<u>Decker #3</u>
		<u>No. 1</u>	<u>No. 3</u>	<u>No. 4</u>	<u>No. 5</u>			
Surface area providing water (m^2)	736	574	438	338	94	632	255,000	
Trickle leaching, mg/d/ m^2	110	90	110	126	148	312	-	
Inundation, mg acid/d/ m^2	11	101	142	88	79	52	-	
Condensation, mg acid/d/ m^2	55	26	4.4	12	36	27	-	
Minimum flows <u>below which:</u>								
-inundation removed no acidity (L/day/ m^2)	1.55	0.76	0.52	0.90	0	0.57	4.31	
-trickle leach removed no acidity (L/day/ m^2)	0.77	0.56	0.26	0.34	0	0.42	0.51	
-condensation leaching was determined to be independent of flowrate								

By converting acidity loadings through the surface area "providing water", which presumably reflects the total exposed surface area, the acid leaching capabilities of unsaturated trickling, inundation, and condensation are found to be of variable relative importance among the case studies. Rates for trickle and inundation leaching of up to 312 mg acidity/day/m² are in agreement with aforementioned laboratory experiments. Rates for condensation leaching are as low as 4.4 mg acidity/day/m² in agreement with corresponding laboratory experiments, although significantly higher rates were more commonly obtained. These values represent rare information on the combined importance of water movement and acid generation from mine walls.

The consistency of the normalized minimum flows for acid leaching despite a wide range of total surface areas (Table 3-4) is notable. However, the applicability of these data to open pits is unknown.

A critical conclusion reached by Morth et al. (1972) was that simulations indicated that hundreds of kilograms of acidity could be stored within the walls of small mines like the McDaniels. The implication for both open pit and underground mines is that stored acidity could cause minewater to become acidic during final flooding and this could be mistaken for active acid generation which may have become negligible. This emphasizes the importance of determining the rate of acid generation and the movement (or lack of movement) of water over the oxidation sites.

4. FIELD STUDIES AT EQUITY SILVER MINES

A primary objective of this study was the field examination of the active Main Zone Pit and the backfilled Southern Tail Pit at Equity Silver Mines in order to obtain detailed information on water movement, acid generation/neutralization, and metal leaching. This information, combined with previous work by Bob Patterson of Equity Silver and his consultants, form the database on which the predictive model of Section 5 is based.

The Minesite is located near Houston, British Columbia. Mining began with the Southern Tail Pit (Figure 4-1) and the site now contains the standard mine components depicted in Figure 1-1. The Southern Tail Pit has since been backfilled with waste rock from the Main Zone Pit and only the upper portions of the eastern pit wall were available for observation at the time of this study. The waste-rock disposal area is currently being expanded in lifts over the Southern Tail backfill until the pit walls are essentially covered.

The Main Zone Pit is nearing completion and this study forms part of the decommissioning plan for it. Due to initially acidic conditions in the Southern Tail Pit during flooding, there is concern that similar acidic conditions could arise in the Main Zone. The potential for the appearance of acidic water would be determined by the rate of acid generation in and on the walls, the direction and rate of water movement, and the effect of possibly placing tailings and waste rock from a third pit into the Main Zone Pit. The impacts of placing tailings or waste rock into the pit were not examined as part of this study.

Due to economically viable ore just north of the Main Zone, a third pit, the Waterline Pit, is in the early stages of development. An insufficient area of pit wall was exposed at the time of this study to allow detailed examinations of the wall and comparisons with the other pits.

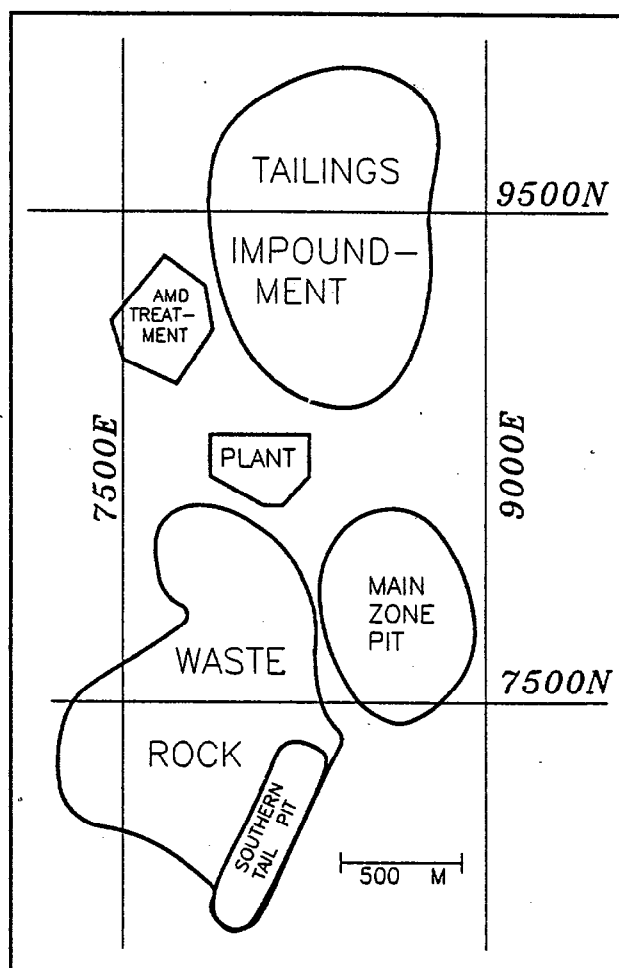


FIGURE 4-1. Generalized Site Plan of the Equity Silver Mine Property.

4.1 Main Zone Pit

At the time of this study, the Main Zone Pit had reached a depth of over 100 meters relative to the western entrance to the pit (Figure 4-2) and the ultimate depth will be less than 200 meters. The pit benches are often 20 meters high, but 10 meter benches are also present. This study and previous studies by Equity Silver Mines have focused on the benches at elevation 1260 meters and higher, because the lower benches were not readily accessible, were close to active mining, and will be submerged upon flooding.

4.1.1 Water movement

Prior to mining, the direction of movement of surface and ground water was likely reflected in the slope of land surface to the southwest and the north-northeast relative to Mine North (Figure 4-3). The Main Zone Pit is located in the upper elevations on the site, presumably in a groundwater recharge zone, with pre-mining flow probably oriented laterally to the west with a vertical component sub-parallel to the land surface. Dewatering of the Main Zone Pit has created a water-table drawdown around the pit (e.g., Figure 3-1) and actively intercepts some recharge to the groundwater system. Due to the sloping land surface (e.g., Figure 3-3), the drawdown is more significant on the eastern side than the western side.

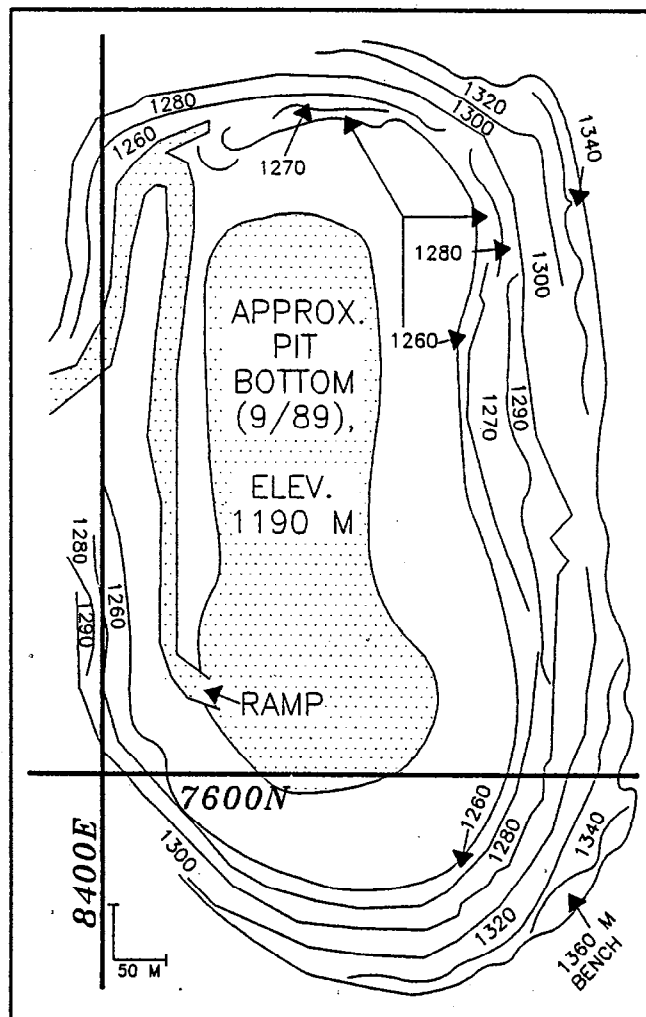


FIGURE 4-2. Plan View of the Main Zone Pit Including Bench Elevations.

In order to define the movement of saturated groundwater in the vicinity of the Main Zone Pit, Equity Silver Mines authorized three key hydrogeologic investigations. The first investigation was a general site overview in 1982 based on nine boreholes with multi-level piezometers (Golder Associates, 1983). The investigation indicated that groundwater recharge in the Bessemer Creek Basin (approximately 12.9 km²) surrounding both pits was: (1) 9 cm/yr over 25% of the catchment having permeable soils for a total of 2.9×10^5 m³/yr, (2) 0.3 mm/yr over 75% of the catchment having till for a total of 2.9×10^4 m³/yr, and (3) 50 cm/yr through the Southern Tail pit floor for a total of 1×10^5 m³/yr. This yielded a total recharge of approximately 4×10^5 m³/yr, although cross-basin flow of groundwater was

not considered. Inflow to the Main Zone Pit was predicted to be $4 \times 10^5 \text{ m}^3/\text{yr}$, or essentially all of the yearly recharge. Such a prediction suggests that the Main Zone Pit would have a basin-wide effect on groundwater levels. This prediction agrees with measured pumping rates in 1987 and 1988 of approximately $5.8 \times 10^5 \text{ m}^3/\text{yr}$.

The second key investigation was a focused field study of saturated groundwater levels and movement near the Main Zone Pit (Sperling, 1985), primarily for slope stability. Based on thirteen piezometers located on the northern, eastern, and southern perimeter, groundwater flow was found to be primarily from the southeast with lesser flow from the east and north. A flownet, presumably based on measured water levels (reproduced in Figure 4-4), shows the relatively steep water table slope to the east. According to hydrogeologic principles for porous media, the steep slope indicates the presence of relatively low-permeability rock, although the fractured nature of the rock could lead to alternative interpretations such as the lack of interconnections among fractures.

On a local basis around the pit perimeter, Figure 4-4 is actually an idealization. The depth-to-groundwater is reportedly within 6 meters of the surface on the south side, 10-20 meters below surface near the east wall, and 15 to >27 meters on the north side.

Sperling (1985) provided additional data on the hydraulic conductivity, fracture characteristics, and compressive strength of the volcanics and gabbro. The gabbro (Gabbro Monzonite, Geologic Unit 6), which occupies much of the east wall of the pit, has a bulk hydraulic conductivity (K) ranging from 9.6×10^{-6} to $1.2 \times 10^{-9} \text{ m/s}$, with the degree of fracturing probably accounting for the range of values. Fracture spacing in the gabbro varies from 0.6-6.0 meters with lengths to greater than 20 meters. In locations on the east wall, the orientation of the fractures results in nearly flat surface planes dipping $50-55^\circ$ into the pit. Uniaxial compressive strength is reported at 455 MPa.

The characteristics of the volcanics (Pyroclastic Division 2A) which form the north, south, and west walls are dependent on the specific sub-group, but the dominant sub-group

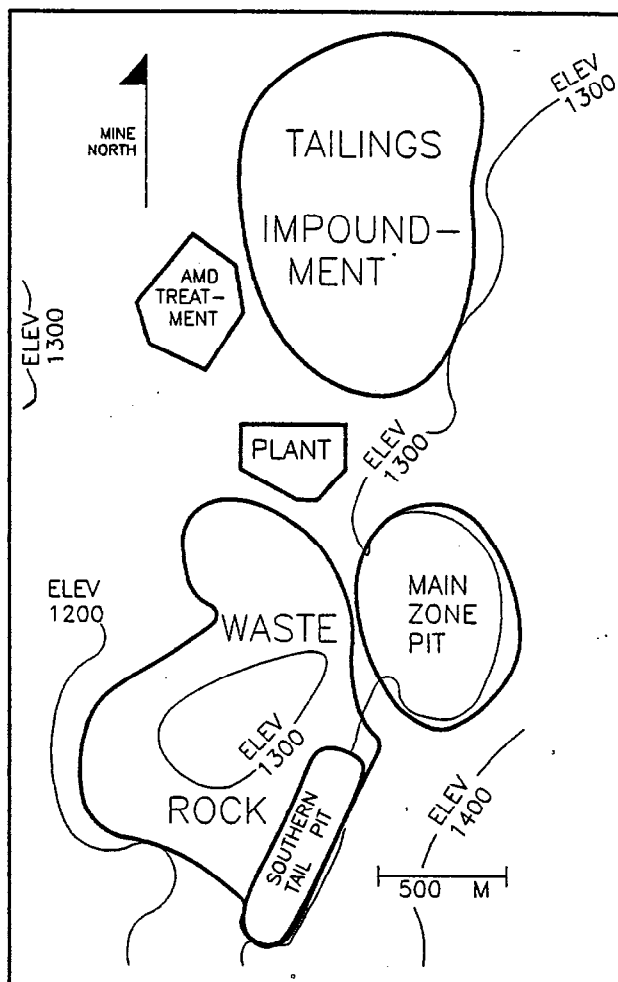


FIGURE 4-3. Plan View of the Minesite with An Elevation Contour Interval of 100 Meters.

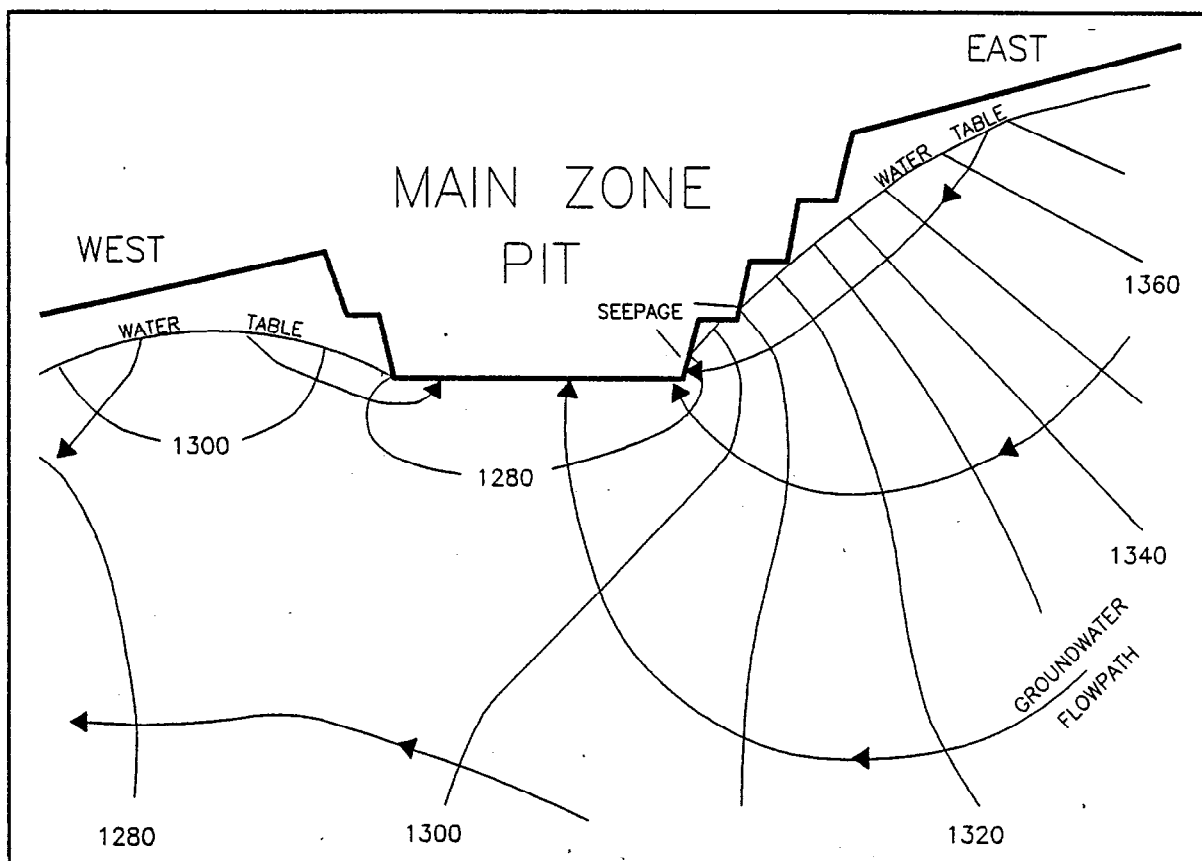


FIGURE 4-4. Groundwater Flownet for the early Main Zone Pit. (Adapted from Sperling, 1985; presumably based on measured data).

is apparently lapilli tuff. This sub-group has hydraulic conductivities of 1.3×10^{-6} to 2.5×10^{-8} m/s, fracture spacings of 0.2 to 0.6 meters with lengths of less than 5 meters, and a uniaxial compressive strength of 112 MPa.

Sperling (1985) felt that drilling may have sealed some fractures during drilling, so values were arbitrarily multiplied by 5 to account for the potential sealing. The accepted values of hydraulic conductivity were:

Gabbro

-weathered or blasted	2.0×10^{-6} m/s
-"intact"	2.0×10^{-8} m/s

Lapilli tuff

-weathered or blasted	1.0×10^{-5} m/s
-"intact"	2.0×10^{-6} m/s

Dust tuff (rare, in lenses <100 meters long)

-intact	7.0×10^{-8} m/s
---------	--------------------------

The higher values for blasted rock reflects the localized "skin" of higher conductivity near mine walls (Section 3). The values selected by Sperling were reportedly close to other measurements made at Equity Silver.

The selected values of hydraulic conductivity and the reported depth-to-groundwater around the pit perimeter account for the variable rate of flow around the pit as reported by Sperling (1985). On the south side, the higher conductivity of the volcanics and the large hydraulic gradient (shallow depth-to-water relatively close to the pit wall) account for the greatest flow of groundwater. The similar conductivity, but significantly lower gradient, explains the lesser flow from the north. The moderate gradient, but relatively low conductivity, accounts for lesser flow from the east side. Although the west side of the pit was not examined during drilling, the presence of volcanics would suggest a moderate conductivity but a minor gradient (Figure 4-4) due to the truncation of most recharge by the pit, resulting in little flow into the pit from this direction. Finally, the upward gradient (around 0.15) beneath the pit (Figure 4-4) provides additional flow into the pit, estimated by Sperling at up to 30% of total pit inflow.

The third key hydrogeological investigation at Equity Silver involved computer simulations (Marlow, 1987). The simulations were rudimentary in that (1) only steady-state conditions were employed, ignoring progressive water table drawdown and release from storage, (2) the pit was simulated through one pumping node in the simulated grid, and (3) only two-dimensional, unconfined flow was simulated while three-dimensional flow is occurring and artesian conditions exist beneath the pit bottom. Additionally, only one value of conductivity (9×10^{-7} m/s) was used for the entire grid. Nevertheless, the simulations indicated that the pumping rate needed to dewater the pit (5.5×10^5 m³/yr) was similar to the pit inflow suggested by Golder Associates (4.0×10^5 m³/yr) and close to the measured pumping rates in 1987-1988 of approximately 5.8×10^5 m³/yr. In comparison to the case studies of Table 3-1, a pumping rate from Main Zone equivalent to 1100 m³/day and a lateral drawdown extent of around 200 meters is not unexpected with a pit area of approximately 400,000 m² and depth of about 100m after a few years.

Simulations by Marlow (1987) suggested that the original elevation of the water table on the west side of the Main Zone Pit was around 1282 meters. This information is critical for predicting the elevation to which the pit may flood during decommissioning (see Figure 3-3) and additional, more thorough simulations are required before a more reliable prediction can be obtained.

The preceding discussion of saturated flow of groundwater near the Main Zone Pit is based on relatively large-scale definitions of flow rates and volumes. On a smaller-scale, groundwater near the pit moves through distinct fracture networks with the shallower networks in an unsaturated condition. There are predominant orientations of fracture sets in the vicinity of the pit and drillholes probably provide hydraulic connections among the networks (Section 3.1), but the complexity of groundwater flow through fracture networks would still yield a random-like pattern of discrete discharge zones on the pit walls.

Sperling (1985) indicated that the dikes located in the Main Zone walls exerted a major influence on local groundwater flow. There is altered gouge along one or both contacts

with the surrounding rock and the observation that most groundwater seepage zones were located near the dikes suggested that the dikes were either high-conductivity channels for groundwater movement or low-conductivity barriers which forced adjacent groundwater to the pit wall.

In order to examine the issue of hydrogeologic impacts of the dikes further, mapping of the Main Zone walls was conducted as part of this study in late September, 1989. One of the three apparent seepage faces was located near the dike on the south side of the pit whereas the other seepage faces were not associated with major dikes (Figure 4-5) and all three faces were located near the bottom of the pit in agreement with the depiction in Figure 4-4. There are several potential explanations for the discrepancy with Sperling's (1985) observation of the hydrogeologic importance of dikes including (1) there are insufficient numbers of seepage faces to determine any association, (2) the major dikes are now above the pit floor whereas they were in the active benches during Sperling's observations, (3) these seepage faces only mark the locations of major inflows whereas much groundwater enters the pit through slower, less obvious seepage, and (4) Sperling's observations may have been made during a wetter season when unsaturated flow or transient saturation of unsaturated fractures may have been significant.

Iron staining is a useful tool for defining past water movement over pit walls. On pit walls where there are no apparent seepage faces, the staining will indicate preferred pathways of acidic water movement. For the Main Zone Pit, the pattern of staining (September, 1989) indicates an association between the dikes and water movement (Figure 4-6). However, caution is warranted in the interpretation because previous maps of iron staining are not available. As a result, the current pattern of staining may indicate (1) saturated seepage faces when the dikes were first exposed, (2)

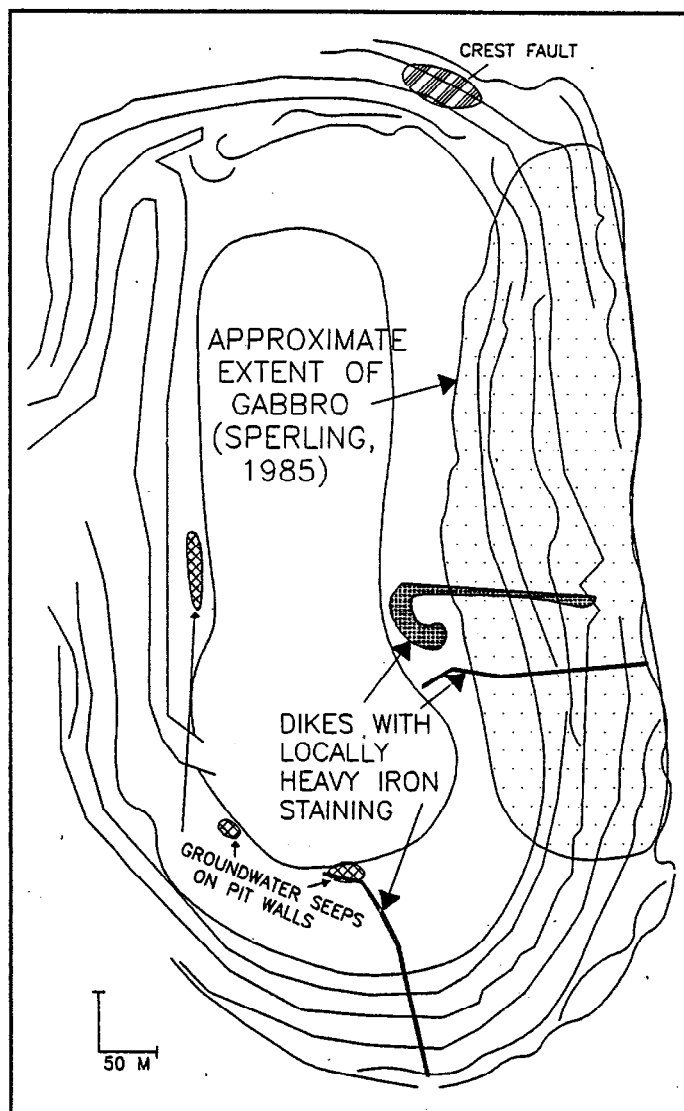


FIGURE 4-5. Locations of Dikes, Faults, and Groundwater Seepage Faces in the Main Zone Pit (September, 1989).

transient flushing of the unsaturated zone near the pit, and/or (3) washing of exposed wall by precipitation.

In conclusion, saturated groundwater flow during operation appears to be consistent with the standard conceptual models (Section 3), based on available information for the Main Zone Pit. There is a consistent pattern of water-table drawdown around the pit which is significantly distorted by the original sloping surface. All predictions and simulations of pit inflow, based on simplified conditions, are in agreement with observed inflows, indicating a relatively simple groundwater flow system. The location of seepage faces only at the base of the pit are also consistent with a relatively simple system.

Iron staining may suggest that seepage faces were more significant in past years when intrusive dikes were first exposed. However, the staining may also be indicative of occasional flushing of the unsaturated zone or washing of wall by precipitation. Due to the lack of past maps of iron staining for comparison, the importance of unsaturated groundwater movement and wall washing can not be assessed. Nevertheless, the following section on

acid generation contains geochemical data which provides some additional information on wall washing. Furthermore, calibration of the predictive model to the Main Zone Pit has provided a reasonably accurate, though indirect, assessment of unsaturated flow through fractures (Section 5.3).

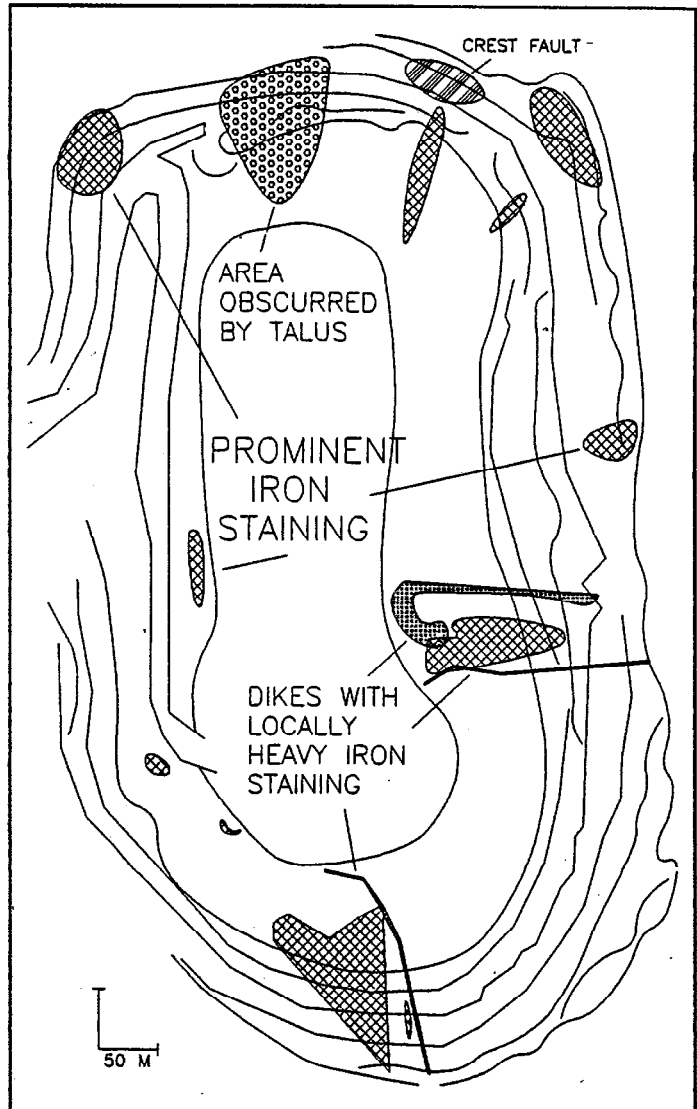


FIGURE 4-6. Locations of Numerous Areas of Prominent Iron Staining in the Main Zone Pit (September, 1989).

4.1.2 Acid Generation and Neutralization

The presence of sulfide minerals in the Main Zone Pit and the observed iron staining indicate sulfide oxidation and associated acid generation is occurring to some degree. As explained in Section 3, the acid products from this oxidation can be carried away from the oxidation sites into an active pit through saturated groundwater flow, periodic flushing of the unsaturated zone, and wall washing by precipitation and groundwater discharge.

For the Main Zone Pit, saturated groundwater flow (Section 4.1.1) has not carried net acidity into the pit. The pH measurements made at seepage faces and a pit sump (Figure 4-7) confirm the neutral to alkaline nature of the inflowing groundwater despite the flow over visual sulfide minerals at the southern seep. Periodic measurements, as well as earlier groundwater data from Golder Associates (1983), also indicate no major change in water chemistry as saturated groundwater flows into the pit (Table 4-1). However, there appears to be a detectable increase in concentrations of some metals by the time groundwater is pumped from the pit, but these differences may be attributed to the addition of wall-wash and fracture-flush water to inflowing groundwater, (discussed further below) or to natural variability of groundwater chemistry with time and location (Annual Reclamation Report, Equity Silver Mines Ltd., 1987).

More detailed measurements of water chemistry through time (Figure 4-8) show that pH of the Main Zone pumpage has generally remained between 7.0 and 8.0, although sulfate displays a trend of increasing concentrations through time, probably reflecting the increasing surface area of the wall exposed to oxidation. Acidity generally decreases through time (measurements terminated in 1987) and alkalinity generally increases, possibly reflecting an increasing reactivity of neutralizing minerals or variations in levels of other elements. Over the same time period, metal concentrations were observed to be generally variable within the ranges of concentrations noted in Table 4-1.

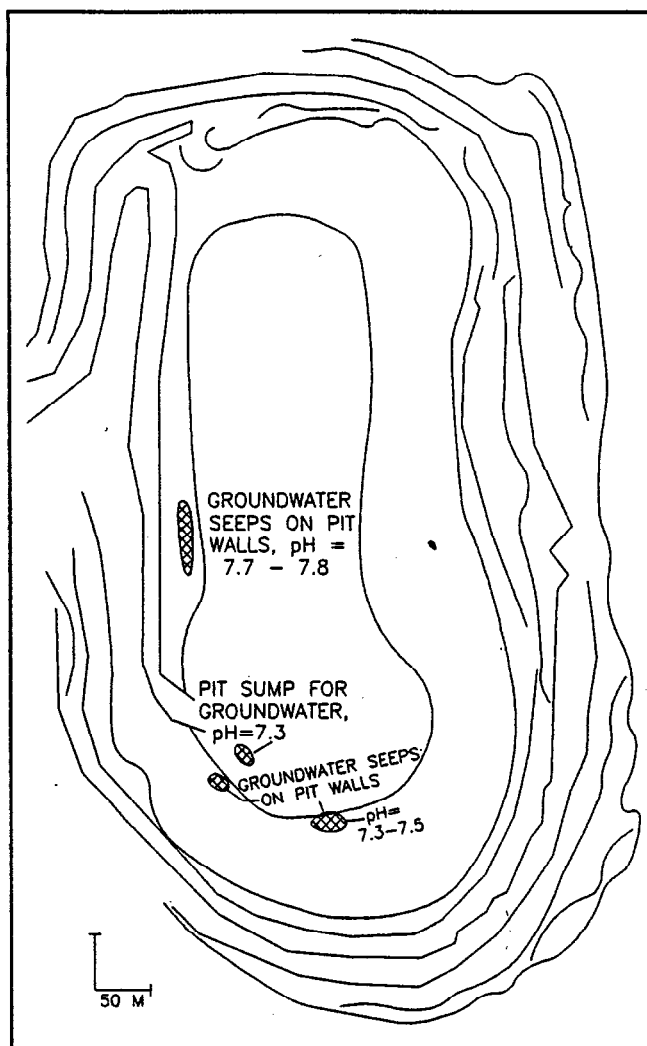


FIGURE 4-7. Values of pH Measured at Groundwater Seepage Faces and Pit Sump (September, 1989).

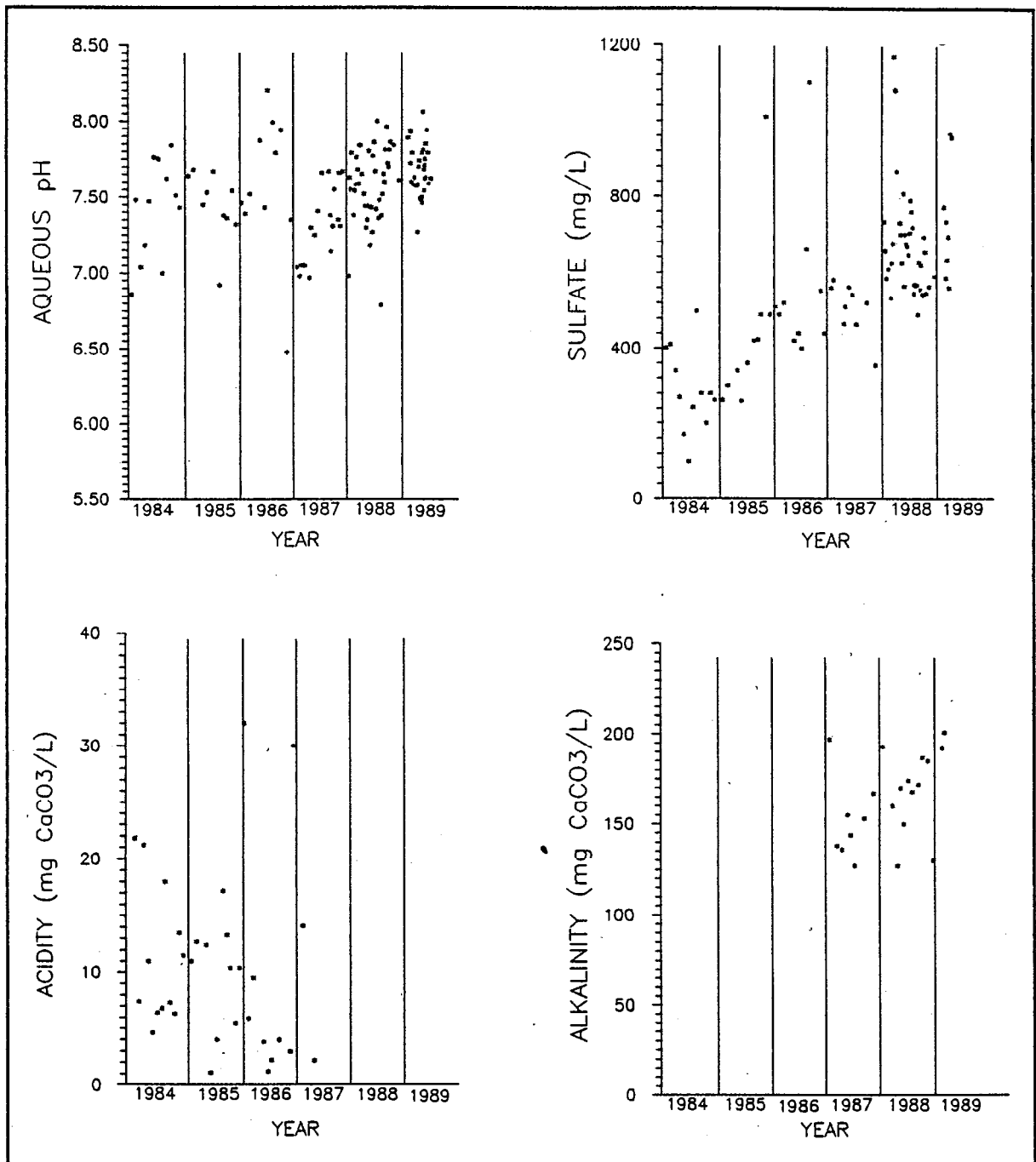


FIGURE 4-8. Water Chemistry of Pit Pumpage from the Main Zone Pit Through Time.

TABLE 4-1
Comparisons of Water Chemistry in Pit Pumpage and Groundwater
in Nearby Saturated Zones

	GROUNDWATER IN: ———			1987 Pit Pumpage ⁴	Total Range Observed ⁵	
	Gabbro ¹	Volcanics ²	Volcanics ³		Low	High
pH	7.6	7.9	7.5	7.3	6.5	8.2
Alk (mg/L)	-	148 ¹	130 ¹	152	127	201
SO ₄ (mg/L)	-	95	830	495	100	1170
Al (mg/L)	-	0.024	0.030	0.014	0.003	0.41
Sb (mg/L)	-	0.0016	0.0007	0.052	0.0025	0.30
As (mg/L)	-	0.0063	0.012	0.013	0.0001	0.074
Cu (mg/L)	-	0.004	0.006	0.025	0.001	0.11
Fe (mg/L)	-	0.11	0.14	0.49	0.01	2.0
Zn (mg/L)	-	0.031	0.012	0.31	0.01	1.2

¹ from Golder Associates (1983)

² 1986 data from Borehole 82-08-02, Table 8-16, A Reclamation Report, 1987, Equity Silver Mines Ltd.

³ 1987 data from Borehole 82-08-03, Table 8-16, Annual Reclamation Report, 1987

⁴ 1987 data from Table 8-18 ("Contract Lab"), Annual Reclamation Report, 1987

⁵ 1984-1989 data from Equity Silver Mines Ltd.; concentrations of alkalinity, aluminum, antimony, arsenic, and cadmium were not measured in all years; most Low values are detection limits.

The observed negligible effect of pit walls on the quality of groundwater flowing into the pit is not necessarily an indicator of future water chemistry during decommissioning when the pit fills with water. At that time, the rising water table will re-saturate the fracture networks and walls that have been exposed to air. Some case studies have indicated that a significant quantity of acidity can be held in the unsaturated portions of mine walls and could be flushed into a mine upon flooding (Section 3.3). For this reason, the geochemistry of the upper benches of the Main Zone Pit which have been exposed longest will play a major role in determining the water chemistry after decommissioning.

As part of this study, four "Wall Stations" were established to determine the spatial and temporal trends in water chemistry from various portions of the Main Zone walls (Figure 4-9). The stations were established by isolating less than 1 m² of pit wall so that the wall and any associated fractures could be thoroughly rinsed and the rinse water collected for analysis (Appendix B). Clear polyethylene sheeting was loosely placed over, but not in contact with the wall, so that (1) precipitation would not wash the areas, (2) condensation would not be artificially induced, and (3) air could flow over the stations. This provided the necessary control to determine the dependence of chemistry on elapsed time since last flush. Because the pit wall at Station 3 is not exposed to vertically falling precipitation and wall wash from higher elevations, the time since last flush is not known, but may be on the order of 100 days (see below).

The stations were rinsed on September 27, 1989, until 500 mL of water was obtained for analysis (Appendix B). Prior to the rinsing, there was 0.2 mm of rainfall on September 21, but this was considered insufficient to thoroughly wash the walls. On September 19, 10.4 mm of rainfall was probably sufficient to remove acid products and leachable metals that had previously accumulated. Consequently, the rinsing at the stations likely reflected 8 days of accumulation (except for the overhanging wall at Station 3). After normalizing

the rate of sulfate production to one day over 1 m^2 of wall, the rates at each station were found to be generally consistent (Table 4-2) except for Station 3. If the rate at Station 3 is assumed to be a more consistent rate of 7.7 mg/d/m^2 , the calculated time to last flush would be 80 days.

The sulfate production rates with an average of 11 mg/d/m^2 are comparable to the lower values of approximately 20 mg/d/m^2 reported for permeable faces of coal in Section 3.2 and are comparable to average rates of about $0.5\text{--}17 \text{ mg/d/m}^2$ from acid-generating rock at the Cinola Gold Project in British Columbia. Rates of acidity from the stations (Table 4-2) are equivalent to or less than the sulfate rate, which reflects the negligible or partial neutralization of acidity by dissolution of neutralizing minerals. As a result, some reported rates of acidity production can not be properly interpreted without correction for neutralization. Similarly, the reported rates of alkalinity production represent excess alkalinity after neutralization. Production of alkalinity and acidity can often be corrected through concentrations of calcium, magnesium, and other relevant metals, but this correction was not critical for this study.

The average rate of sulfate production of 11 mg/d/m^2 (Table 4-2) is critical for predictions of acid generation (Section 5). The rates of alkalinity production are not quantitatively important for predictions, but confirm that neutralizing minerals on the wall and fractures are reactive and result in both a pH above 4.8 and measurable alkalinity.

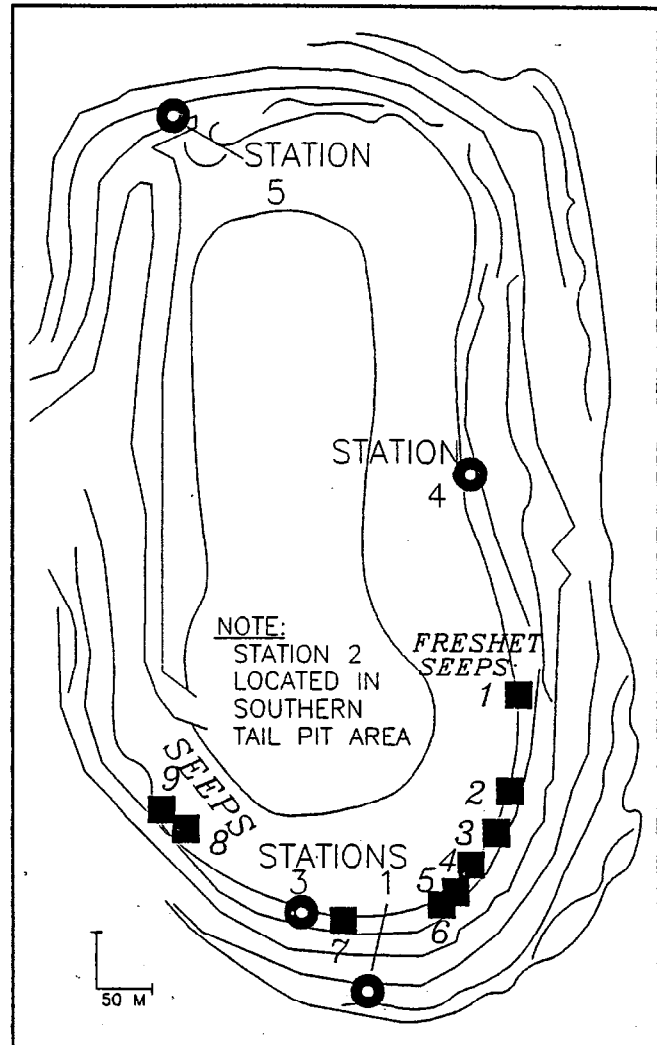


FIGURE 4-9. Locations of Wall Stations (Circles) and Freshet Seeps (Squares) in the Main Zone Pit.

TABLE 4-2
Production Rates of Sulfate, Acidity, and Alkalinity
from the Wall Stations¹
 (rates in mg/day/m²)

<u>Parameter</u>	<u> -- S T A T I O N -- </u>				<u>Station</u> <u>No. 3²</u>	<u>Station</u> <u>No. 2³</u>
	<u>No. 1</u>	<u>No. 4</u>	<u>No. 5</u>	<u>Nos. 1,4,5</u>		
Sulfate	7.1	6.9	19.0	11.0	76.9	29.1
Acidity	7.7	2.3	2.4	4.1	0.52	1.5
Alkalinity	1.9	0	8.7	3.5	3.1	1.0

¹ based on data in Appendix B, corrected on the basis of concentrations in the blank sample; time from last flush = 8 days

² the rates for Station 3 are based on the 8-day accumulation, but actual time from last flush is probably much greater

³ Station No. 2 is located in the Southern Tail Pit

In addition to acid generation, metal leaching can have a significant impact on water chemistry. During metal leaching, concentrations typically increase in the leaching water until an equilibrium concentration is obtained. This equilibrium concentration is a function of variables such as pH, the presence and concentrations of other elements, and temperature. Also, the time to reach the equilibrium concentration may be on the order of days at neutral pH so that metals may be flushed away before equilibrium is attained. As a result of such complications, metal concentrations can be highly variable, but maximum equilibrium concentrations should eventually appear in periodic analyses.

The attainment of equilibrium metal concentrations in the rinses from the Stations cannot be confirmed with available information, but the similarity of aqueous concentrations in the rinses (Table B1) despite differences in exposed surface area and the greater time-of-accumulation at Station 3 suggests that the values in Table B1 are close to or at equilibrium. Conversion of these concentrations to production rates like those in Table 4-2 would incorrectly place a significant and continuous time dependency on the metal leaching. This issue of metal leaching will be discussed further in Section 5.

The four Stations in the Main Zone Pit provide valuable, but spatially and temporally limited, information on acid generation within the pit. The limitations can be overcome by periodic rinsing of the Stations for chemical analysis. Equity Silver Mines is considering at least one additional rinse at the Stations within the next year. However, for the purposes of this study, the limited data from the four Stations will be supplemented by data on freshet seeps on the pit wall and acid-base accounting.

Chemical analysis of nine wall seeps during spring snowmelt have been previously

reported by Equity Silver Mines Ltd. (1988, p.47C). These seeps were reportedly water flowing down the wall at specific locations on the 1260-meter bench (Figure 4-9), rather than actual groundwater discharges from fracture networks, but flushing of some shallow fractures probably occurred as this water flowed downwards. Because the surface area flushed by each seep and the time since last flush are not known, concentrations cannot be normalized as in Table 4-2. Nevertheless, comparisons of aqueous concentrations of metals (Table B2, Appendix B) indicate that seep concentrations near neutral pH (7.9-8.0) are generally similar to those from the Stations, again indicating the general attainment of equilibrium concentrations of metals at neutral pH. These neutral seeps are located on the east gabbro and southeast sides of the pit. The pH and chemistry of acidic seeps (Nos. 8 & 9, pH=2.8-3.0) and of the transitional seep (No. 7, pH=6.3) located on the south side are consistent with the commonly observed, higher levels of metal leaching at acidic pH as well as the higher rates of acid generation (sulfate production) needed to overcome neutralization and maintain an acidic pH. These seeps also demonstrate a dependence of acid drainage on location within the pit, which is a critical issue for a reliable prediction of future water chemistry within the pit.

The spatial dependency of potential acid generation in the Main Zone Pit has been evaluated through acid-base accounting (ABA). For the Decommissioning and Closure Plan (Equity Silver Mines Ltd., 1988), a total of 159 samples were collected from intervals around the Main Zone perimeter on the benches at elevations 1280, 1300, 1320, 1340, and 1360 meters (Figure 4-10). Twelve of the samples were duplicates and six samples were specific lithologies within selected intervals (Appendix C).

The samples were analyzed for total sulfur, neutralization potential, and paste pH. Total sulfur was converted to "Maximum Potential Acidity" (MPA) in units of tonnes of CaCO_3 equivalent/1000 tonnes of rock through multiplication by 31.25. This conversion has implicit limitations, most notably that all sulfur

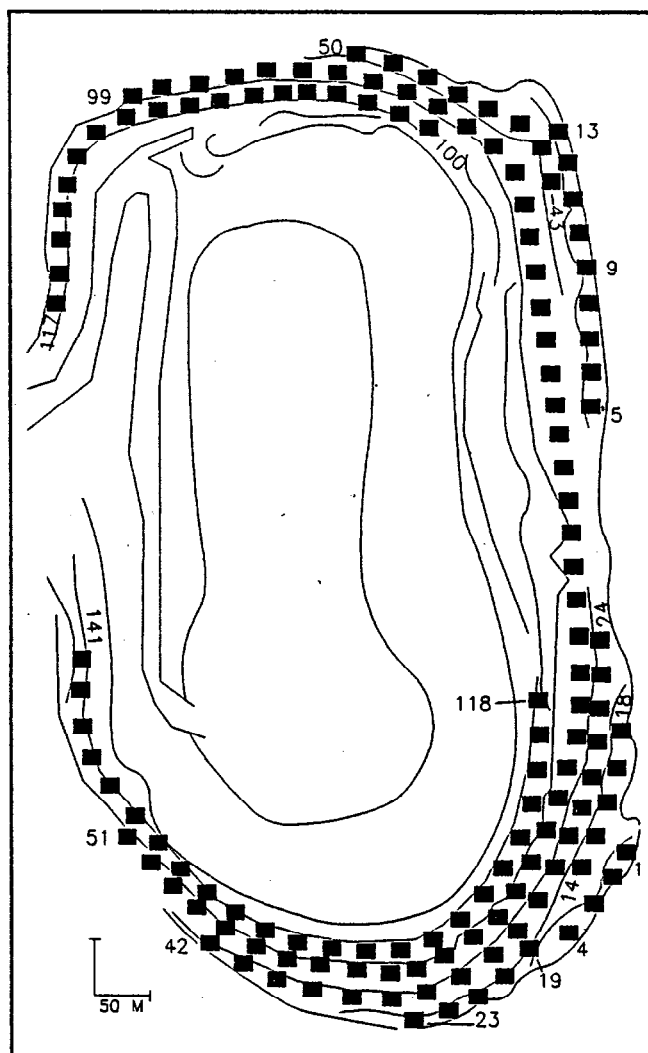


FIGURE 4-10. Locations of Intervals From Which Samples Were Collected for Acid-Base Accounting. Sample Numbers Correspond to Data in Appendix C.

will generate acidity although some visible sulfide minerals showed little signs of oxidation (Appendix B). Neutralization Potential (NP) was measured through a titration procedure which determines the content of strongly neutralizing carbonate minerals and less neutralizing hydroxide/oxide minerals. By subtracting MPA from NP in equivalent units of $t \text{ CaCO}_3/1000 \text{ t}$, the "Net Neutralization Potential" (NNP) is obtained. A negative value of NNP theoretically indicates the potential for net acid generation after some period of environmental exposure, whereas a positive NNP indicates a net capacity to neutralize acidity in most situations. Due to the limitations and assumptions of the ABA procedure, the actual critical value separating net acid generation from net neutralization is site-specific and may be a negative or positive value of NNP. Paste pH is measured by grinding the sample, mixing a small amount of water with the rock, and measuring the pH of the paste. The resulting pH is a general indicator of the extent of acid generation prior to analysis and the reactivity of neutralizing minerals.

Twelve duplicate samples of selected intervals were analyzed by an alternative method to determine the reproducibility of ABA parameters (Appendix C). The accuracy of NP and MPA measurements and NNP determinations were calculated to be 2.68, 2.23, and 3.17 $t \text{ CaCO}_3/1000 \text{ t}$, respectively. The differences between the methods were biased towards negative values, indicating that the differences probably reflected the differing laboratory procedures rather than the random error of analysis.

The specific lithologies within selected intervals were analyzed for comparison with the bulk interval (Appendix C). Results indicated that specific lithologies within an interval could have significantly different ABA characteristics than the bulk values, but one lithology (presumably representing the largest portion of the bulk sample) has similar ABA characteristics to the bulk sample. For the purposes of this study, the bulk values for each interval are taken as reflecting the weighted average of the lithologies with the intervals.

A comparison of all ABA analyses of NP to NNP (Figure 4-11) shows that many samples have negative values of NNP despite the presence of significant neutralization potential, that is, greater than $10 t \text{ CaCO}_3/1000 \text{ t}$. When compared to paste pH, values of NP less than $10 t \text{ CaCO}_3 / 1000 \text{ t}$ were found to have pH values between 4.3 and 8.8 (Figure 4-12), indicating sulfide oxidation had overcome the reactive neutralizing minerals in some samples. In other samples the relatively small amounts of neutralizing minerals were still reactive and maintaining neutral pH. The prognosis for the pH-neutral samples with NP values $< 10 t \text{ CaCO}_3/1000 \text{ t}$ is that the reactive minerals may soon be consumed and

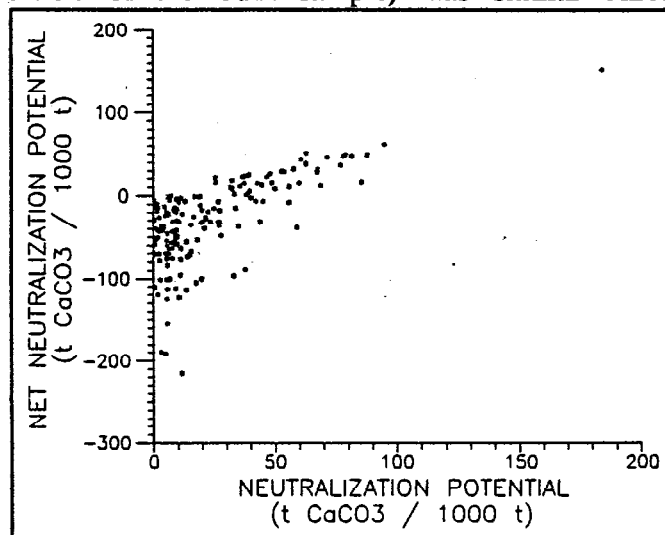


FIGURE 4-11. Net Neutralization Potential vs Neutralization Potential in the Main Zone Pit.

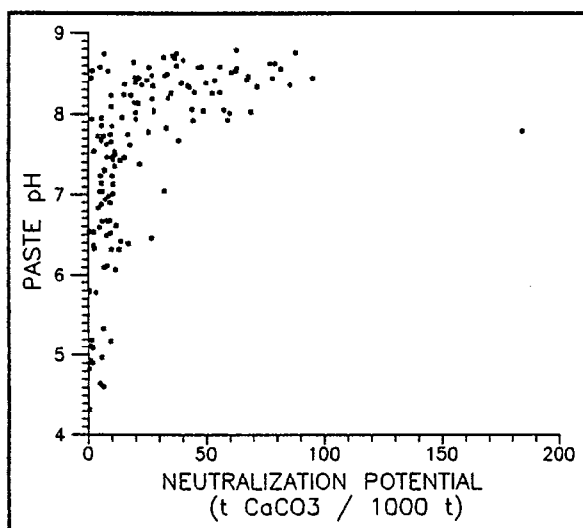


FIGURE 4-12. Paste pH vs Neutralization Potential.

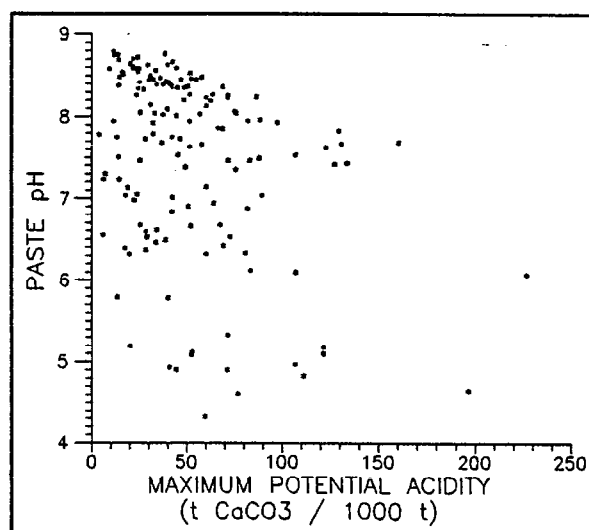


FIGURE 4-13. Paste pH vs Maximum Potential Acidity.

acid drainage may then begin. For NP values greater than 10 t CaCO₃/1000 t, paste pH is often greater than 7, indicating that the neutralizing minerals are probably reactive carbonate minerals and in sufficient quantity to maintain neutralization for a relatively long period of time. The consumption of NP is a critical consideration for proper predictions (Section 5). A similar comparison of MPA (calculated from total sulfur) shows no clear trend with paste pH (Figure 4-13). This indicates that paste pH is independent of total sulfur content.

For predictive purposes, a quantitative relationship must be defined between ABA parameters and water quality, particularly aqueous pH. This relationship will be established below, but it is interesting to note that in lieu of aqueous data, a relationship can be established between NNP and paste pH (e.g., Figure 4-14). However, paste pH is not directly comparable to aqueous pH and paste pH is not indicative of long-term acid generation and neutralization. Consequently, such a relationship should only be used in desperate situations and resulting predictions should be interpreted only in general terms. For the Main Zone ABA analyses, the relationship of paste pH to NNP can be numerically described by:

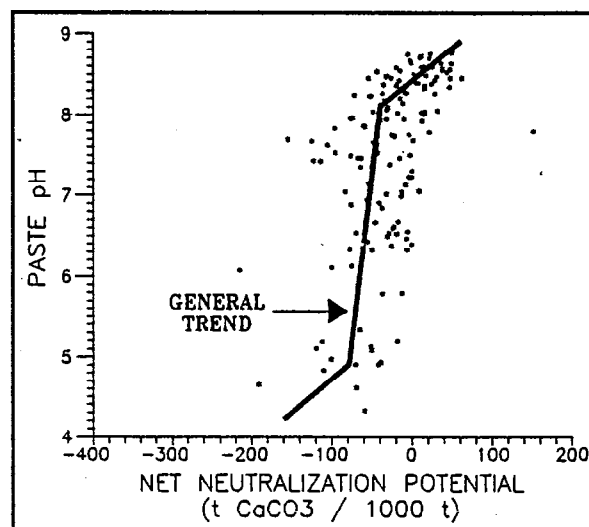


FIGURE 4-14. Paste pH vs. Net Neutralization Potential.

NNP > -40 t CaCO₃/1000 t:

paste pH = $8.10 + (\text{NNP} + 40) * 0.008$

-80 < NNP < -40 t CaCO₃/1000 t:

paste pH = $4.90 + (\text{NNP} + 80) * 0.080$

NNP < -80 t CaCO₃/1000 t:

paste pH = $4.90 + (\text{NNP} + 80) * 0.00875$

Because ABA parameters are variable around the pit perimeter, contouring of ABA parameters based on interval location (Figure 4-10) will highlight the current and possible future locations of net acid generation. Contouring of the ABA parameters has been performed for this study using a computerized statistical/graphics program and the contour lines have been statistically extended to lower benches.

Contour values of paste pH (Figure 4-15) show that the upper benches on the northwestern and south-southwestern sides of the pit have the lowest paste pH (near Station 5), presumably due to excess acid generation. Additionally, the southern portion of the west wall also has a depressed paste pH. Some of the large iron stained areas (Figure 4-6) originate in or near these areas of low paste pH.

A comparison of paste pH with aqueous pH values from the Stations and Freshet Seeps (Figure 4-9) indicates the existence of a generally good, but not linear, correlation of paste and aqueous pH for the Main Zone Pit. The acidic Seeps 8 and 9 are located on the southwestern side of the pit, Seep 7 with the transitional pH is located on the south side where paste pH is increasing rapidly towards the east, and the remaining, pH-neutral seeps are located on the eastern and southeastern walls. Stations 5 and 3 with pH around 6 are located lower on the northwest and southern wall within elevated paste-pH zones. Station 1 with an aqueous pH of 4.9 is located high on the southern wall where paste pH is depressed. Station 4

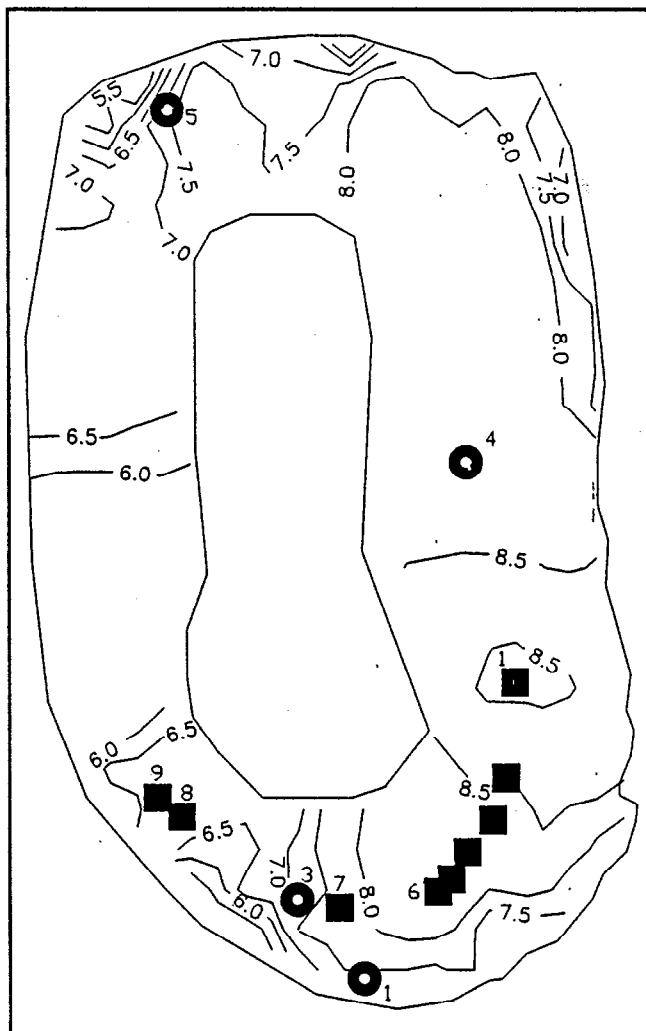


FIGURE 4-15. Contour Diagram of Paste pH in the Main Zone Pit.

in gabbro on the east wall has a relatively low aqueous pH of 5.0, but is located in an area with a paste pH greater than 8, thus representing the only major anomaly between aqueous and paste pH. Most of the areas of iron staining are located in regions with transitional values of paste pH, suggesting that acidic iron water originates in the acidic areas then migrates into neutral-pH regions where it is neutralized and iron is precipitated on the wall.

The spatial distribution of paste pH in Figure 4-15 is consistent with the distributions of other ABA parameters. The locations of low paste pH correlate with areas of low neutralization potential (Figure 4-16) and high maximum potential acidity (Figure 4-17). Station 4, with the anomalous relationship between aqueous and paste pH, is located in the area of lowest NP and highest MPA in the gabbro on the east wall. Also, this is the area where intrusive dikes and a large iron-stained area are present (Figure 4-6). Consequently, aqueous pH at Station 4 appears to be consistent with trends in MPA and NP and with iron staining, indicating that paste pH appears to be a non-reliable parameter for identifying acid generation within the gabbro on the east wall. However, paste pH is of little importance to the predictive model (Section 5).

The final major parameter summarizing all field data and predictive capability of ABA is net neutralization potential around the pit perimeter (Figure 4-18). The distribution of net neutralization potential indicates that only portions of the northeastern and southeastern walls have positive values of NNP and are thus not expected to generate net acidity at any time. Even if limitations of ABA procedures and interpretation indicated that an optimistic value of $-20 \text{ t CaCO}_3/1000 \text{ t}$ represented the critical value for net generation of acidity, the non-acid generating regions of the wall would not change significantly in area.

The trend along the south wall of more positive values of NNP from west to east was predicted by Sperling (1984) with ABA analyses of drill core. This

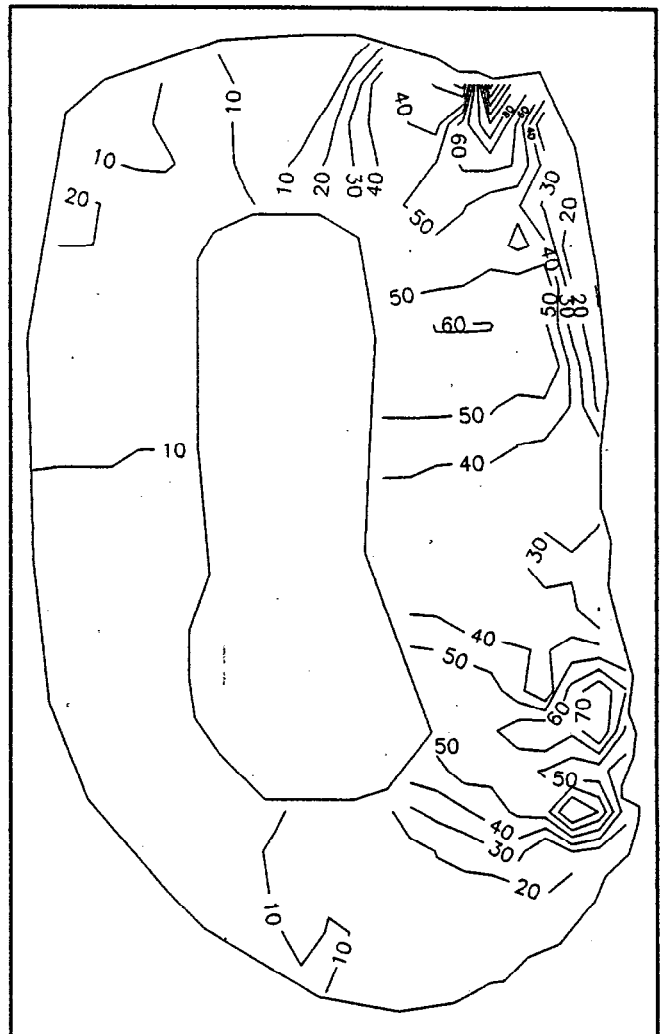


FIGURE 4-16. Contour Diagram of Neutralization Potential ($\text{t CaCO}_3/1000 \text{ t}$) in the Main Zone Pit.

predictive capability adds additional weight to the importance of obtaining ABA analyses prior to mining (Section 6.2.1) for predictions of pit-wall impacts on water chemistry.

Based on a NNP value of 0 t $\text{CaCO}_3/1000 \text{ t}$ as the critical value for net acid generation, all Stations and Freshet Seeps except Seeps 1 and 2 are located in areas of potential net acid generation. Because Seeps 1-7 and Stations 3 and 5 are associated with neutral aqueous pH, the conclusion is drawn that NNP indicates future (long-term) potential for net acid generation, but NP is the short-term indicator of net acid generation in the Main Zone Pit.

In summary, the correlation between aqueous pH, the ABA parameters of NP, MPA, and paste pH, and iron staining provides a large, integrated database on short-term acid generation in the Main Zone Pit. With the kinetic rates of acid generation (sulfate production) measured at the Stations, detailed predictions of pit-water chemistry are now possible (Section 5). The ABA parameter of NNP does not correlate well with other data, but may act as a long-term indication for net acid generation providing (1) all sulfur can generate acidity and (2) the oxidation rate of all sulfur remains relatively high through time. Both conditions are unrealistic for the Main Zone Pit and are discussed further in terms of the predictive model (Section 5).

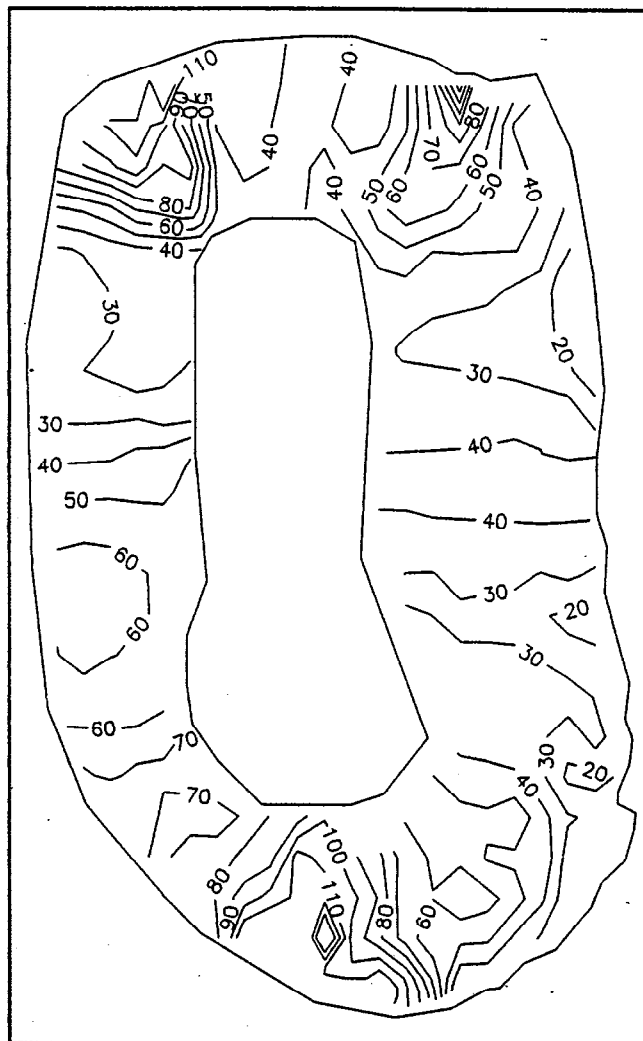


FIGURE 4-17. Contour Diagram of Maximum Potential Acidity (t $\text{CaCO}_3/1000 \text{ t}$) in the Main Zone Pit.

4.2 Southern Tail Pit

Although it is not a primary focus of this study, an examination of water analyses from the Southern Tail Pit at Equity Silver serves two purposes. Firstly, the Southern Tail Pit represents another case study of geochemical events during pit flooding, only a short distance from the Main Zone Pit which will also soon be flooded. Secondly, the backfilling of Main Zone waste rock into the initially acidic pit waters of the Southern Tail yields information on metal leaching and the reactivity of the Main Zone neutralizing minerals under acidic conditions. The neutralizing minerals were found to be critical in the short-term water chemistry in the Main Zone (Section 4.1.2) and thus provided alkalinity to the Southern Tail during flooding.

Mining in the Southern Tail Pit was completed in May, 1984. Water-quality information beginning in January, 1985, indicated that pH of the pit water was initially neutral, decreasing to values around 3 by mid-1985 (Figure 4-19). Backfilling with waste rock from the Main Zone Pit, shown to have reactive neutralizing minerals by acid-base accounting and water-chemistry interpretation, began in October, 1985.

Within a few months, pH had risen to almost 6, dropped again to below 3.4, then increased to around 7 by the end of backfilling in October, 1986. Since that time, pH values have varied from about 7 to greater than 8.

The development of acidic conditions as the pit began to fill may be attributed to the combination of flushing stored acid products on the walls and within the unsaturated fracture networks downward to the pit bottom and the decreasing flow of alkaline groundwater into the pit. One Wall Station, similar to those in the Main Zone to monitor acid generation and metal leaching, was established on the north end of the west wall (Station 2, Appendix B). The rate of acid generation (sulfate production) from this Station was higher than those within the Main Zone (excluding ambiguous results from Station 3, Table 4-2), probably due to the more porous nature of the wall rock at the Station and/or higher sulfide levels. An excavation of the wall near Station 2 revealed a series of closely

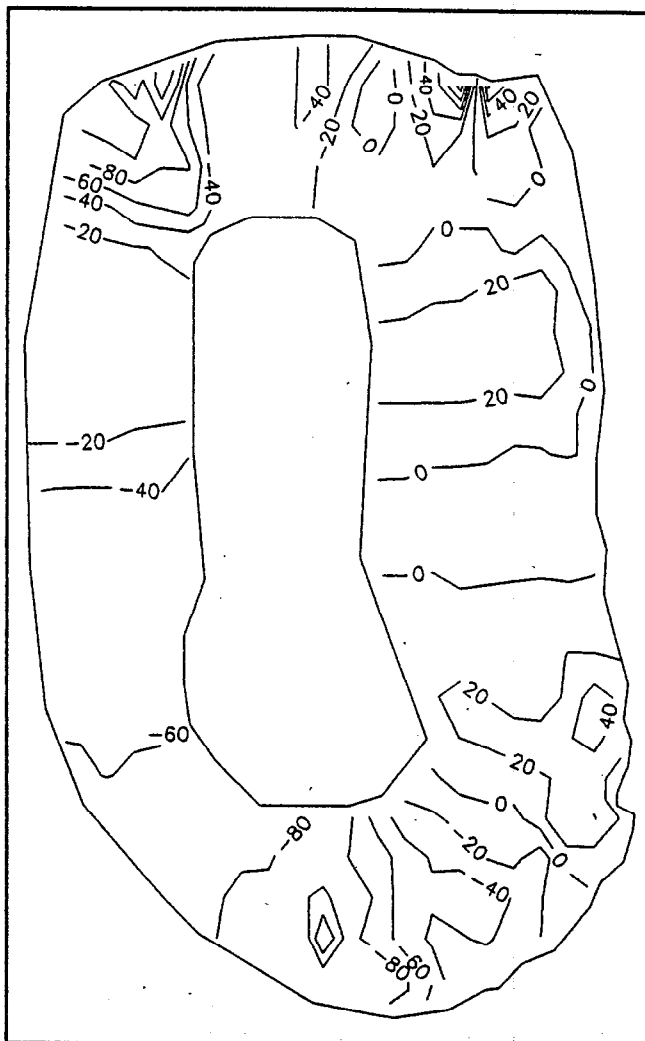


FIGURE 4-18. Contour Diagram of Net Neutralization Potential (t CaCO_3 /1000 t) in the Main Zone Pit.

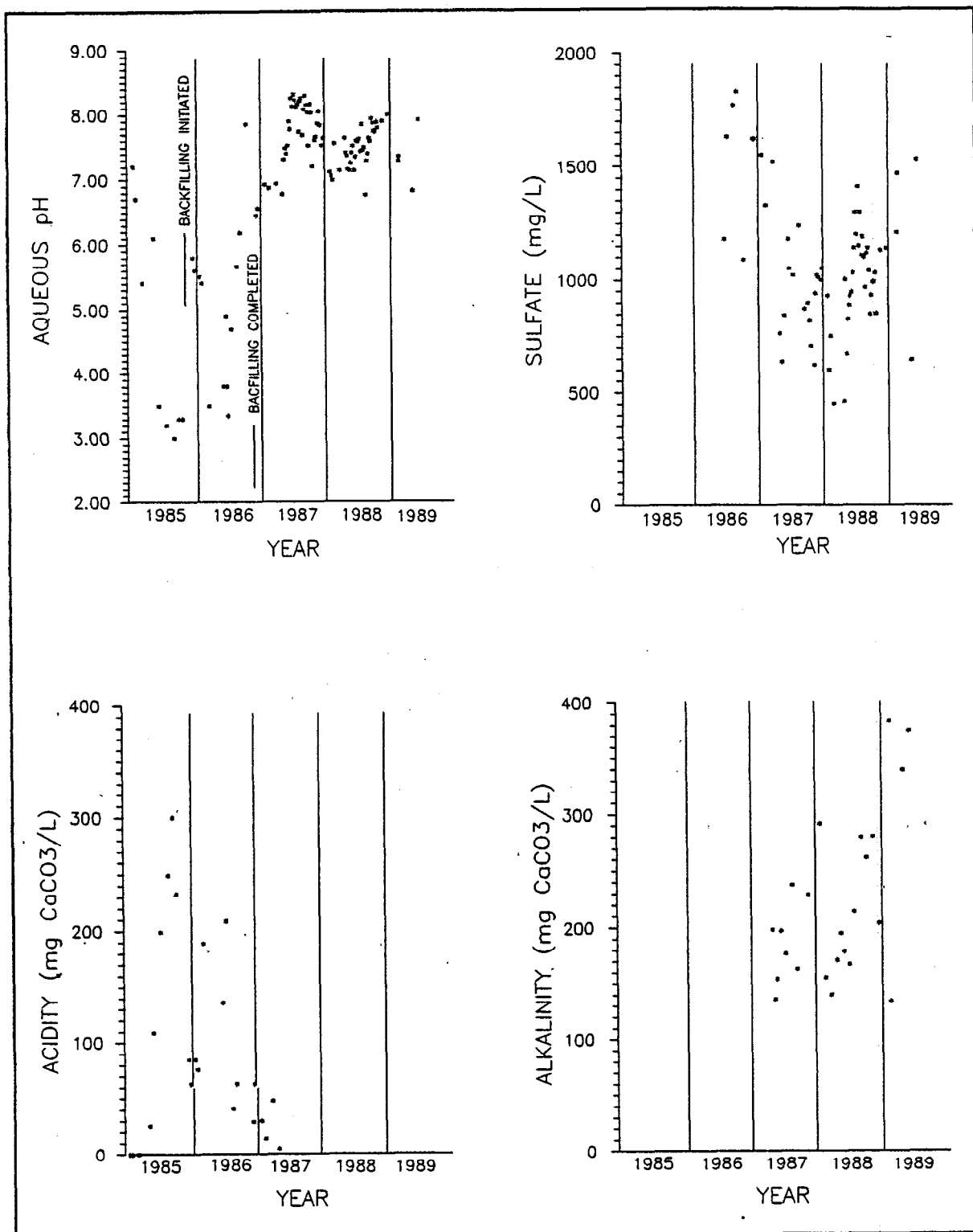


FIGURE 4-19. Time vs pH, Sulfate, Acidity, and Alkalinity in Southern Tail Pit Water.

spaced fracture planes parallel to the wall and the staining found on all planes indicated recent acid generation (Appendix B). These fractures oriented parallel to the wall may have represented a large storage capacity for acidity, which could account for the sharp drop in pit pH following mining.

Corresponding sulfate concentrations showed an initial decrease, then increase, beginning in mid-1986 (Figure 4-19). This trend may reflect effects such as gypsum precipitation as calcium-based carbonate minerals dissolved in response to acidic pH or dilution. Trends in acidity and alkalinity through time (Figure 4-19) corresponded to the rise in pit-water pH.

Metal leaching was enhanced at acidic pH and concentrations of copper, iron, and zinc reached levels of 13, 19, and 17 mg/L, respectively, prior to pH neutralization at later times. As the Main Zone waste rock neutralized pH in the pit water, minerals containing these minerals likely precipitated, regulating metal concentrations to significantly lower levels (Figure 4-20). Despite pH values greater than 7, concentrations of these metals were found to still vary by over 1 order of magnitude, which probably reflects either (1) variable equilibrium speciation of the metals with complexes of sulfate, carbonate, and hydroxide, (2) variable non-equilibrium leaching rates, or (3) dilution. Nevertheless, these ranges of concentrations are similar to those found in the Main Zone Pit (Table 4-1), nearby groundwater (Table 4-1), and the Wall Stations (Table B1). Additionally, the aqueous metal concentrations from Station 2 are similar to those from other Stations. All of these similarities probably indicate the operation of equilibrium-based geochemical controls on metal concentrations at near-neutral pH.

After pit water in the Southern Tail Pit had been neutralized by the Main Zone rock, analyses for arsenic, antimony, aluminum, and cadmium began (Figure 4-21). Because of the late implementation of analyses, metal concentrations over a large range of pH were not available. However, equilibrium-based geochemical reactions probably also regulate concentrations of these metals at near-neutral pH. As with copper, iron, and zinc, the concentrations of arsenic, antimony, aluminum, and cadmium were similar in values to Main Zone water (Table 4-1) and the Wall Stations (Table B1).

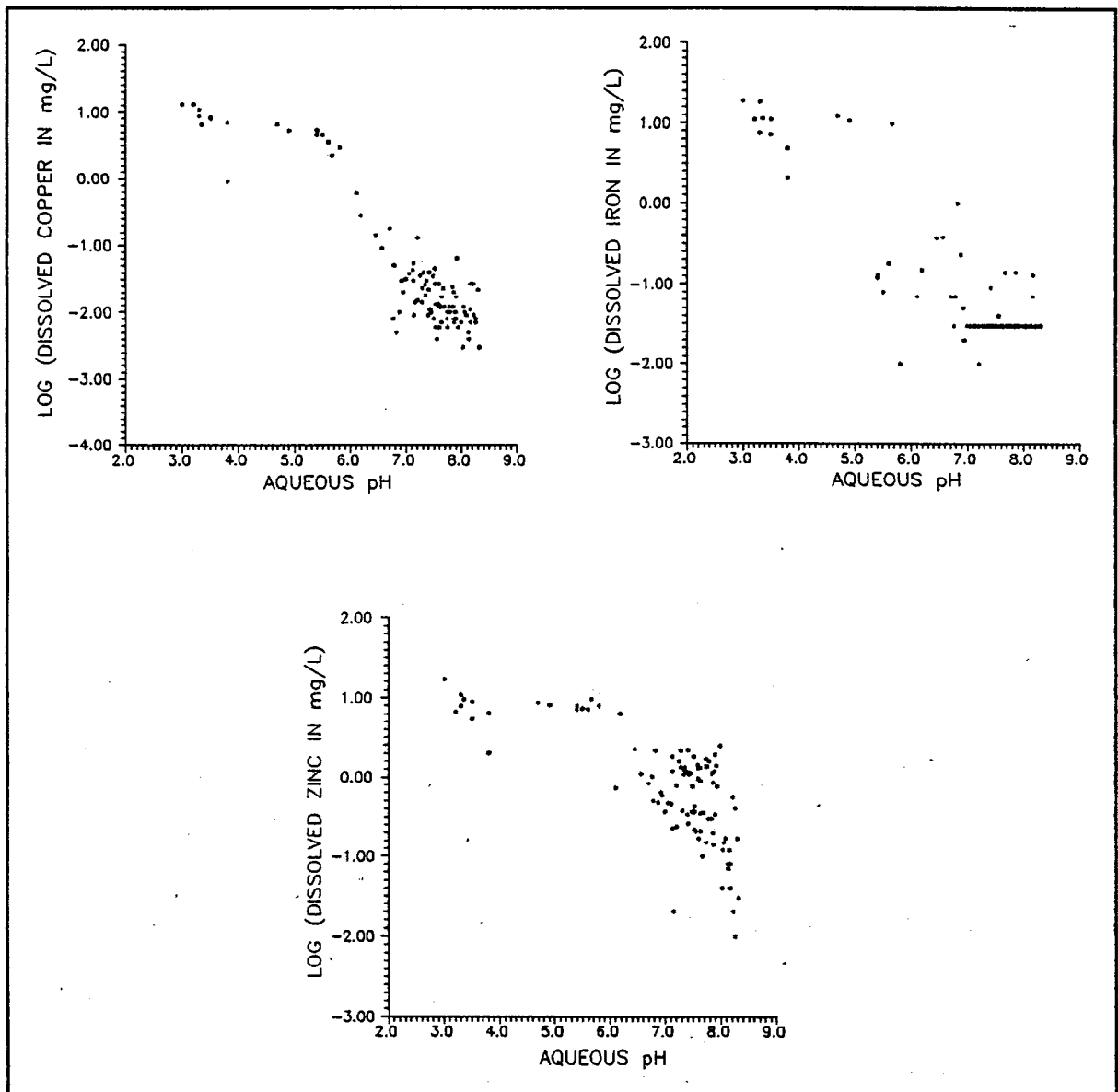


FIGURE 4-20. Aqueous pH vs Copper, Iron, and Zinc in the Southern Tail Pit.

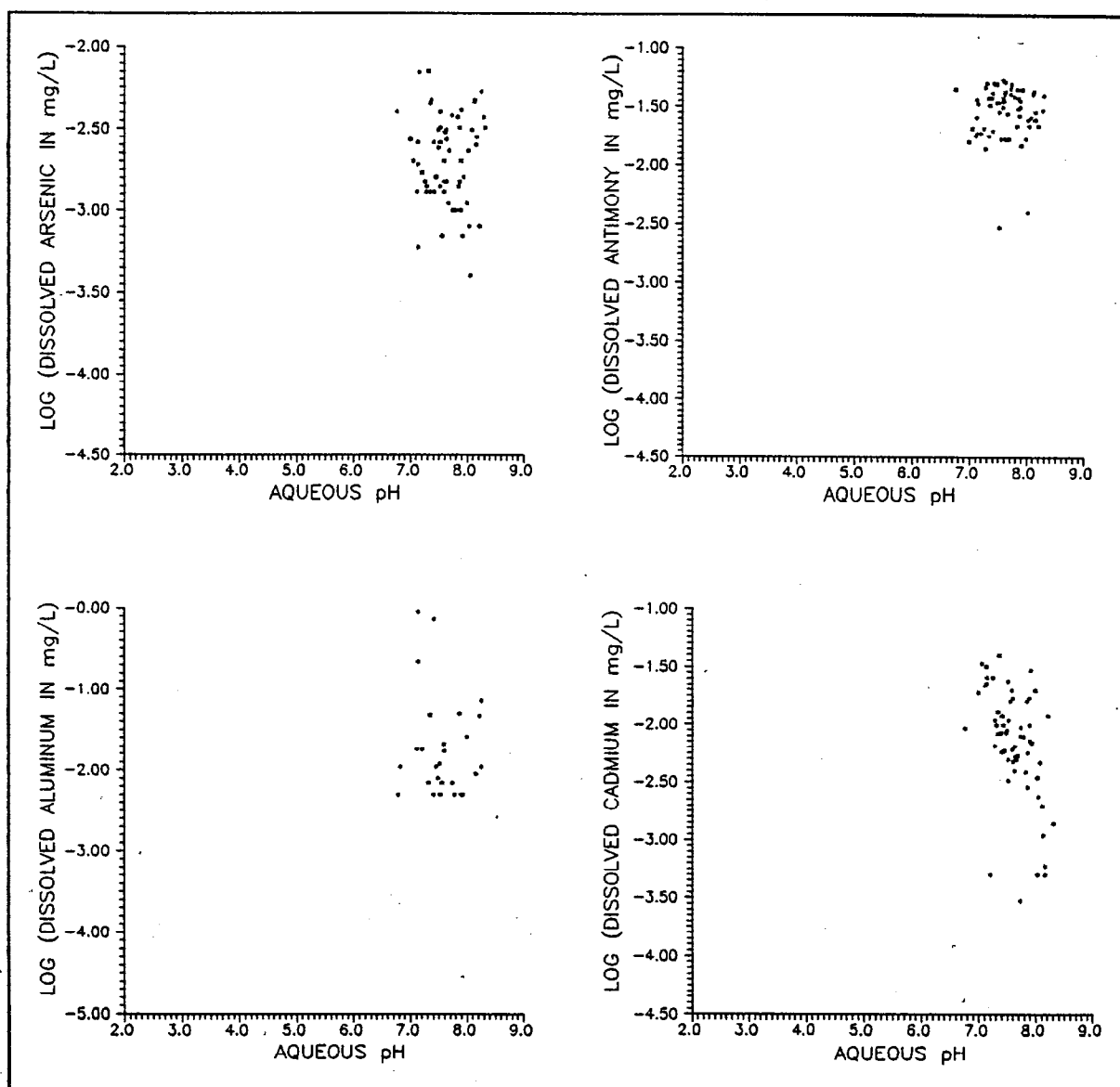


FIGURE 4-21. Aqueous pH vs Arsenic, Antimony, Aluminum, and Cadmium in the Southern Tail Pit.

5. PREDICTIVE MODEL

In addition to the literature review and the evaluation of site data, the third primary objective of this study was to create and utilize a computer program to simulate the Main Zone Pit during operation, flooding and decommissioning. This section of the report describes (1) the conceptual models behind the simulations, (2) the computer program named MINEWALL which is a mathematical implementation of the conceptual models, and (3) the results of MINEWALL simulations for the Main Zone. The results indicate whether acidic or pH-neutral water can be expected in the Main Zone Pit through time.

5.1 Conceptual Models

The conceptual models on which MINEWALL is based account for water movement, acid generation, acid neutralization, and metal leaching through time within a mine. These models highlight parameters which are important for properly describing and simulating open pits. However, the literature review and Equity data evaluation have demonstrated that no currently reported study has addressed all of the critical issues identified by these models. As a result, the description of any open pit in terms of the models and MINEWALL depends to some degree on indirect, sometimes inaccurate, sources of information such as calibration to existing conditions and estimation of data.

5.1.1 Conceptual Model for Water Movement

The basis for the conceptual model of water movement is depicted in Figure 3-1 for the phase of active operation and in Figure 3-3 for flooding and decommissioning. These diagrams show that there are three primary sources of water: precipitation implicitly including runoff, unsaturated groundwater flow, and saturated groundwater flow. The important variables identified by the models for each of these modes of water transport are discussed below.

The volume of water movement, originating as precipitation, over a rock unit on a pit wall is dependent on the surface exposed to the precipitation, the angle of the exposed surface from horizontal, and the variable rate of precipitation. Because horizontal benches are common in most pits, a rock unit may have surfaces exposed in both horizontal and sloping orientations. According to the requirements of the model, all of these variables must be defined for each rock unit with distinct characteristics. Exceptions arise during flooding when a submerged rock unit is no longer exposed to precipitation.

Water movement over walls is often more complex than implied above because flow over sloping walls may not be equivalent to flow over benches and the pit bottom. For example, this could arise in late winter when the walls may be covered with ice. Any rainfall would not contact the walls, but simply run over the ice to the underlying bench. The model must then account independently for water movement over surfaces exposed as either sloping wall, horizontal bench, or pit bottom.

Groundwater (subsurface) flow occurs predominately through fractures in most metamorphic and igneous rock and the model thus concentrates on the physical characteristics of, and water movement through, these fractures. Flow through porous media, though not explicitly included in the model, can be simulated by adjusting parameters such as fracture-surface area.

Groundwater flow through the saturated zone is oriented into the pit during operation and active flooding, and through the pit after the water level has reached an equilibrium level. This flow will usually vary monthly and yearly as infiltration and water levels fluctuate. In regions with rock of relatively high hydraulic conductivity, the saturated flow will likely account for most of the water moving into or through the pit.

The two primary factors regulating saturated flow are hydraulic conductivity and hydraulic gradient. Conductivity is enhanced locally around the wall (Section 3.1), but this probably does not significantly increase regional flow. Conversely, gradients (water levels) can be affected for distances of up to tens of kilometers (Table 3-1) and thus hydraulic gradient is often the major factor in determining variations in saturated flow. As a result, regional groundwater investigations and simulations are required to properly define and predict saturated flow through time. Alternatively, saturated flow can be estimated to some degree by subtracting the water movement over walls, benches, and pit bottom and the movement by unsaturated flow from the total pit pumpage during operation or the pit volume (during flooding).

The most complex mode of water movement is unsaturated flow through fractures, which is also often the most important mode for geochemical reasons (Section 5.1.2). The complexity becomes apparent when envisioning the movement of precipitation as it infiltrates through the land surface above the pit and through benches and walls and then drains downward with some lateral movement through horizontal and vertical fracture networks, which may be interconnected or isolated. Furthermore, unsaturated fracture surfaces may be flushed with water on a regular basis, only during wet seasons, or not at all during operation. The surfaces not flushed during operation play a key role in determining water quality during flooding and decommissioning. Despite the difficulty, all of the aforementioned parameters must be addressed to properly describe and simulate a pit in terms of the conceptual model and MINEWALL. As will be shown in Section 5.3, the estimation of fracture flushing for the Main Zone Pit was accomplished through calibration to existing data.

During flooding of a pit, the water table rises and submerges fracture networks. If these networks are interconnected, they then become part of the saturated flow system, which is more easily defined and simulated. Critical parameters for the conceptual model during decommissioning and flooding are: (1) the rate of water inflow to the pit during flooding, which will generally decrease through time, (2) the relationship of water storage in the pit and surrounding rock vs. water level, and (3) the equilibrium level to which the pit will flood. As explained earlier, the rates of water flow and the equilibrium level should be predicted with regional investigations and simulations.

5.1.2 Conceptual Model for Acid Generation, Neutralization, and Metal Leaching

The basis for the conceptual model of acid generation and neutralization is depicted in Figure 3-4. Acid generation from sulfide oxidation occurs on the surface of grains and blocks of rock as well as internally. For mine walls, a more convenient conceptualization is of a wall surface broken by fracture planes. Acid generation then occurs on the mine wall, on the fracture planes within the wall, and within the block of rock defined by the fractures. Additionally, acid generation can occur on broken rock that has accumulated on benches. For metamorphic and igneous rock, oxidation within a block is usually minor because of the negligible internal permeability to water and air. Rates of acid generation on exposed surfaces can then be determined through procedures such as the Wall Stations discussed in Appendix B. Such procedures should be repeated periodically because the rate of oxidation often decreases with time to a negligible value or increases if the neutralization potential is depleted.

For long-term predictions of acid generation, the quantity of exposed, reactive sulfide on a unit area of surface must be determined. This can be conveniently done through on-site observations and acid-base accounting results. Through on-site observations, the small depth into the surface which is available for oxidation is noted (such as 1-2 mm for the Main Zone Pit, Appendix B) and this depth multiplied by the exposed surface area to obtain a volume. The measurement of reactive sulfur from acid-base accounting then indicates the portion of this volume available for acid generation. An implicit assumption in this approach is that the sulfur is distributed evenly throughout the rock, but adjustments can be made for irregularities in the distribution such as veins.

If the reactive sulfur is exposed on submerged fracture surfaces, the rate of oxidation may be negligible and can thus be ignored in the application of the conceptual model. As exposed sulfur oxidizes in the unsaturated fractures, the resulting acidity will either be flushed away by frequent flushing, by periodic washing after some accumulation, or will be retained. Any retained acidity remains readily available for later flushing, which would play a critical role in determining water quality as a pit (or underground mine) fills with water.

As long as both moisture and oxygen are readily available, the rate of sulfide oxidation on the exterior wall and within the internal fractures will often be similar when normalized to a unit area of surface. If either moisture or oxygen are limited, then the rate of acid generation will decrease. Limitation of moisture is dependent on climate and seasonal variations; however, most climates in Canada will probably not lead to moisture limitation. Limitation of oxygen on mine walls can occur during submergence, whereas limitation of oxygen in internal fractures can occur from both submergence and consumption of oxygen as it diffuses into an internal fracture. Studies at the Ohio State University (Section 3.3) indicated that oxygen consumption at a rate greater than supplied by diffusion limited the amount of acid generation in a fracture to the region closest to the mouth of the fracture. Barometric pumping was predicted to enhance the movement of oxygen into such a fracture only to a minor degree. Other limitations such as temperature will be discussed in later sections.

For this conceptual model, an equation predicting acid generation from an oxygen-limited fracture was considered critical. Related equations and constants for a porous medium from Morth et al. (1972) were corrected and adapted to a fracture within impermeable rock. The resulting equation for acid generation within one fracture with a length of L meters on the wall and unlimited depth into the wall (i.e., sulfur is always available within the fracture) is:

$$AG = 2[R/F - (R/F \times \text{EXP}(-F \times L))]$$

where AG = rate of acid generation in 1 fracture in mg SO₄/day
 R = maximum oxidation rate (Equity=11.0 mg SO₄/day/m²)
 $F = (K/D)^{1/2}$
 K = reaction rate in day⁻¹ ($2.0 \times 10^{-6}/V$, Morth et al.)
 V = gas volume in fracture (m³) exposed to 1 g of pyrite
 D = 0.6 x DA
 DA = normal O₂ diffusivity in air in appropriate units
 L = length of fracture trace on wall in meters

Much of the preceding discussion on acid generation holds for acid neutralization as well, except reaction rates. The neutralization of acidic water by calcium-based carbonate minerals is often relatively rapid so that it can usually be considered an instantaneous response to acid water. The exposed carbonate minerals on the wall and fracture surfaces will typically dissolve until excess alkalinity is present in the water, which implies that carbonate can be consumed in quantities greater than indicated by sulfate or acidity alone. As long as a rock unit contains sufficient excess carbonate over potential acid production, the water flowing over the rock surface will remain near neutral pH.

The quantity of exposed carbonate on a surface can be calculated through the procedure described above for exposed sulfur (second paragraph of Section 5.1.2), except that carbonate content or neutralization potential is used in place of reactive sulfur. On-site observations will indicate whether the carbonate is disseminated throughout the rock or is localized in veins or vugs. In lieu of detailed mineralogical analyses, the default assumption would be that the ratio of exposed sulfur to exposed carbonate equals the ratio from the bulk acid-base accounting.

A critical component which supplies acid-neutralizing alkalinity from a distant source is the flow of groundwater from the saturated zone. For example, the Main Zone Pit has monthly flows of tens of millions of liters with an alkalinity of approximately 150 mg CaCO₃/L. This represents a significant quantity of neutralization which can neutralize acidity being leached from walls and internal fractures during operation and decommissioning. This fact further emphasizes the importance of regional groundwater investigations and simulations for reliable predictions of groundwater inflow and flooding (see also Section 6.2).

Metal leaching is a complex process which is dependent on such variables as pH, time, temperature, and the concentrations of other elements. If metals are leached until an

equilibrium concentration is attained, the equilibrium concentrations typically are strongly dependent on pH. Consequently, the conceptual model for metal leaching assumes that equilibrium concentrations are attained and that the concentrations are dependent solely on pH, which in turn is determined from excess acidity or alkalinity as discussed above.

5.2 MINEWALL Coding, Operation, and Verification

The conceptual models from Section 5.1 were mathematically interpreted and coded into a computer program, named MINEWALL. This program is written in standard Fortran 77 and is suitable for execution on most sizes of computers. The executable program is approximately 80K bytes in size.

MINEWALL begins a simulation by asking for a short title. It then asks for the average length of time that the walls have been exposed prior to the beginning of the simulation. This eliminated the need to run a simulation from the beginning of mining. The program asks for the total time of the simulation in months, which is the smallest time unit used by MINEWALL. The option of simulating just operation or both operation and decommissioning is offered. If operation and decommissioning are chosen, the elapsed month at which flooding begins is then requested.

Next, MINEWALL requests details on the rock units. This includes the number of distinct rock units, the orientation of the units, the exposed surface areas, the extent and angle of sloping walls, and the area of the pit bottom.

MINEWALL then requests data on monthly values of precipitation for a typical year. These data are then repeated for each simulated year. Options are offered for input of alternative values for the sloping walls, the horizontal benches, and the pit bottom.

Typical monthly inflows of groundwater from the saturated zone are requested by MINEWALL. These values are repeatedly used for each simulated year until flooding begins. Unsaturated fracture flow in each rock unit for each month of a typical year is then required. As discussed in Section 5.1.1, these values can be difficult to determine without detailed field investigations.

The next topic addressed by MINEWALL is acid generation. For each rock unit, the program requests rates of acid generation on a monthly basis to allow for seasonal variation and freezing of the oxidation sites during winter. Rates are inputted in units of mg $\text{SO}_4/\text{month}/\text{m}^2$ and are specifically for an exposed surface of 1 m^2 not including any internal fractures associated with the surface. During execution, MINEWALL assumes that 2 moles of acidity are generated for each mole of sulfate. This may overestimate the generated acidity because the ratio has been found in limited experiments on British Columbia hard rock to be between 1 and 2.

The inputted rates are assumed to decrease at an arbitrary rate of 5%/year each year due to effects such as the consumption of finer-grained sulfide minerals. This causes the oxidation rate to decrease asymptotically to zero: the oxidation rates after 10 and 50 years

are 59.8% and 7.7% of the original rates, respectively, if reactive sulfur is still present. This approximation is considered to overestimate the rate in later years, but some type of decay of rates is realistic under many conditions. On the other hand, the oxidation rate is known to be pH-dependent and could actually increase through time. This effect is not currently accounted for by MINEWALL. In any case, this approach can only be refined by using long-term results from site-specific kinetic tests and field tests such as Wall Stations (Appendix B).

Sulfide oxidation is permitted by MINEWALL until all reactive sulfur is consumed. For each rock unit, the program requests the quantity of exposed sulfur on each 1 m² of mine wall in units of grams S/m². These values can be calculated by following the procedure described in Section 5.1.2.

MINEWALL then turns to acid generation within internal fractures. The rate can be determined by in-field experiments with forced fracture flushing, although such experiments have apparently not been reported in the published literature, or by approximate predictive equations such as the one developed in Section 5.1.2. Due to the general lack of data regarding acid generation in fractures, MINEWALL simply asks for the total oxidizable fracture surface in m² that is associated with each 1 m² of mine wall in each rock unit. The rates of oxidation in the fractures are assumed to be identical to the preceding values for the wall.

The next critical issue is the percentage of fracture surface of each rock unit that is flushed monthly, yearly, and not at all during operation. The sum of the three values for each unit must equal 100% and the month during which the yearly flush occurs must be specified. During simulations of the Main Zone Pit (Section 5.3), these values were found to have major impacts on simulated water chemistry during operation and decommissioning. The values can be adjusted until the simulated chemistry is similar to observed chemistry during operation. However, this approach incorporates all other uncertainties and errors into the process of fracture flushing.

In order to simulate acid neutralization, MINEWALL requests the background concentration of alkalinity in unsaturated and saturated flows of groundwater prior to entering the mine. The background value of alkalinity in saturated flow was found to be critical in simulated results of the Main Zone Pit. Any background concentrations of sulfate are also requested and are simply added to the sulfate from acid generation in the mine.

As the final input for simulation of the operational phase, MINEWALL requests the quantity of exposed neutralization capacity on 1 m² of pit wall not including any internal fractures. These values must be in units of grams CaCO₃/m² and can be calculated in a similar manner to exposed sulfur (Section 5.1.2). Each square meter of any internal fracture surfaces is assumed to have the same quantity as the mine wall. Alkalinity is released to any water moving over a surface so that an arbitrary excess alkalinity of 50 mg/L is created if sufficient exposed neutralization capacity is present.

MINEWALL first calculates the total amount of sulfur and alkalinity released each

month and divides each value by the total volume of water in the system, yielding concentrations of acidity, sulfate, and alkalinity. In a subroutine, MINEWALL calculates pH based on any excess of acidity over alkalinity based on the measured relationships in the Main Zone and Southern Tail Pits (Figure 5-1). Data from both pits were used for Figures 5-1 so that a relatively large range of pH values would be included. The depicted relationship demonstrates that acidity is close to zero whenever excess alkalinity exists in the water. According to the best-fit equation, aqueous pH has a value of 7.57 whenever excess alkalinity occurs and decreases in a non-linear fashion as excess acidity increases. Better estimates of pH can be obtained with a speciation model that considers all relevant aqueous complexes and solid-liquid interactions; however, complete water analyses and other detailed geochemical data are required as input, but not available for the Equity Silver pits. The inclusion of a speciation routine in MINEWALL is one direction for further enhancement of the program.

After pH is calculated, the concentrations are calculated for copper, iron, and zinc, which are the only metals with concentrations measured over a wide range of pH (Figures 5-2 to 5-4). Near neutral pH, metal concentrations are essentially independent of pH and are more strongly dependent on other factors such as aqueous complexing and mineral solubility. For this reason, predictions of metal concentrations by the current version of MINEWALL should be considered only general in nature, but could be improved by the inclusion of a speciation routine.

If the user requests simulation of flooding and decommissioning, MINEWALL begins by asking for (1) the steady-state flow of water through the pit after flooding is complete in units of m^3/month , (2) the equilibrium level of the water when flooding is complete in meters above sea level, and this value is assumed to be constant throughout the year, (3) the elevation of the pit bottom when flooding begins, and (4) the elevation of the pit crest, which can be greater than or equal to the equilibrium water level. If the pit crest is higher, acid generation and neutralization are allowed to continue on the exposed surfaces, whereas these processes are terminated when a surface is submerged. However, during the first month of submergence, a surface is flushed of any acidity that accumulated during operation.

MINEWALL then asks for the relationship of water level to water storage in the pit. Beginning at an elevation 20 meters above the pit bottom and continuing at 20 meter intervals, the storage capacity of the pit and surrounding unsaturated rock must be provided in units of m^3 . Through a complex interrelationship, MINEWALL calculates the water level for a new month by adding the calculated inflow to the existing water in the pit and obtaining the level from the total volume then in the pit. If the level exceeds the specified equilibrium level, the equilibrium level is implemented.

In reality, the monthly rate of inflow varies seasonally and decreases through time as the mine fills. Detailed hydrogeologic simulations are required to determine the variations in flow, but MINEWALL approximates the variation in inflow by first subtracting the flow through the pit at equilibrium from the average monthly inflow during operation. This difference is assumed to disappear as the water level rises using an exponential-related equation. This equation specifies, for example, that 44% and 82% of the difference

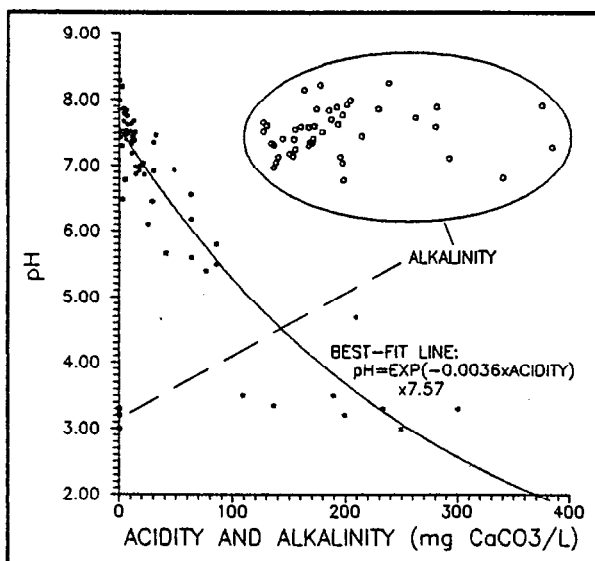


FIGURE 5-1. Acidity and Alkalinity vs pH in the Main Zone and Southern Tail Pits.

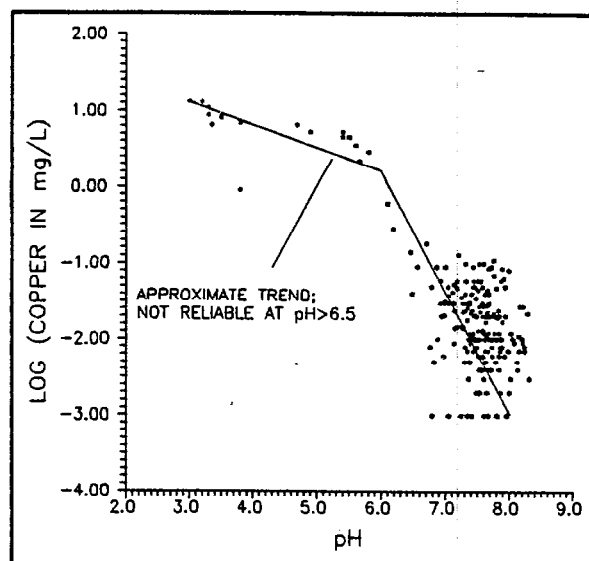


FIGURE 5-2. Copper vs pH in the Main Zone and Southern Tail Pits.

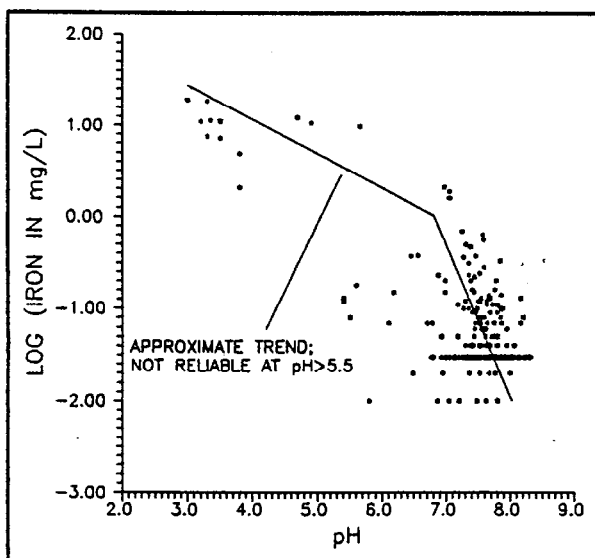


FIGURE 5-3. Iron vs pH in the Main Zone and Southern Tail Pits.

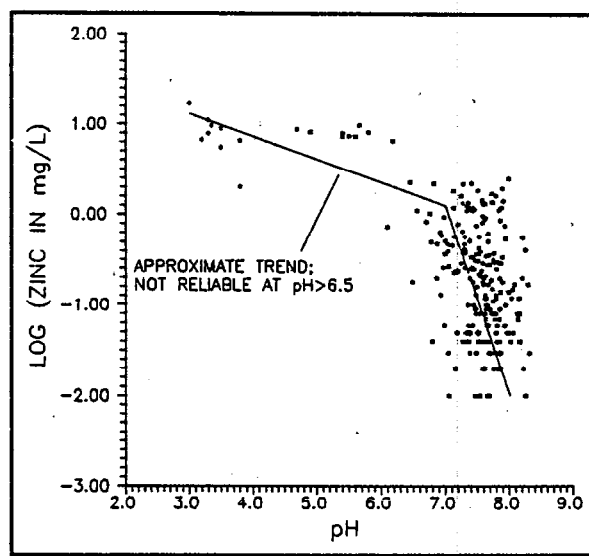


FIGURE 5-4. Zinc vs pH in the Main Zone and Southern Tail Pits.

disappears when the water level reaches 50% and 75% of the equilibrium level, respectively.

The final issue examined by MINEWALL is the flooding of rock units. If the orientation of the rock units is specified as vertical extending from pit crest to bottom, MINEWALL assumes the fraction of each rock unit flooded each month is determined by the ratio of the monthly rise in water level to the total distance from crest to pit bottom. In essence, this is a simple linear simulation of flooding. If the rock units are oriented as horizontal bands around the wall, MINEWALL requests the elevation in meters above sea level of the top of each rock unit with Unit #1 at the top of the pit. MINEWALL then monitors which unit is actively flooding at a particular time and the percentage of the unit flooded on a monthly basis.

These aforementioned data can be entered into a input data file using the Format statements in MINEWALL (Appendix D) or by using the preprocessor program, PREMINE. PREMINE introduces each topic of input with a discussion and rationale and then asks for required data. The necessary units are indicated. PREMINE is written in standard BASIC rather than Fortran due to BASIC's easier input/output handling. PREMINE has been tested by creating various data files and submitting these files to MINEWALL. PREMINE has been compiled to render it language-independent.

MINEWALL is written in standard Fortran 77 and has been successfully compiled with the Microsoft Optimizing Fortran Compiler v.4.0. The executable code has a size of around 80K bytes and is thus easily executed on computers with only 120K of RAM memory.

As a preliminary validation of MINEWALL, portions of the computer code have been visually rechecked. Also, some variables have been monitored during trial executions using Microsoft's Codeview Debugger in order to identify coding errors. Finally, any seemingly unusual results were evaluated for validity. Based on more than 40 trial executions, the code appears to be free of significant errors. However, validity of the results can only be confirmed through more extensive testing, verification, and documentation, which are beyond the objectives of this study. Consequently, MINEWALL should be considered rudimentary at this time and not ready for general use.

5.3 Application of MINEWALL to the Main Zone Pit

MINEWALL was used to simulate the operation and decommissioning of the Main Zone Pit. Based on acid-base accounting and geology, three rock units were identified (Table 5-1) with many of the characteristics of each unit determined from maps and field observations. Exposed sulfur and CaCO_3 were calculated from acid-base accounting, maintaining the ratio of the average bulk analysis, with an oxidation depth of 2 millimeters based on observations (Appendix B). The oxidizable surfaces of internal fractures were calculated from reported fracture spacings and with the arbitrary assumption of oxidation to 10 meters along the fractures. This depth of oxidation is in general agreement with field observations in the Main Zone of more than 4 meters (Appendix B) and with 15

meters from the case study of the McDaniel Mine (Section 3.3). The percentages of fracture surfaces flushed monthly, yearly, and not during operation represent the best-fit values as explained below. The rate of acid generation (sulfate production) for all rock units was specified as 334.6 mg SO₄/month/m² (11.0 mg SO₄/day/m², Table 4-2) during the months of March through November. During the remaining months, the walls and shallowest parts of the fractures are frozen, minimizing the rate and surface area of acid generation. For these months, the average rate was arbitrarily assumed to be 10% of the full rate.

Water flows were calculated by comparing precipitation to pit pumpage using 1989 data (Table 5-2) which are considered more reliable than data from previous years due to the termination of backflushing during pumpage. Precipitation was adjusted for the walls and benches by assuming that there is no flow over these surfaces during winter months, but that recorded snowpacks in the area accumulated on these surfaces.

TABLE 5-1
Input Data for the Simulation of the Main Zone Pit

	<u>Unit #1</u>	<u>Unit #2</u>	<u>Unit #3</u>
Basis for unit:			
-geology	Gabbro	Volcanics	Volcanics
-acid-base accounting	NNP > 0	-40 < NNP < 0	NNP < -40
Orientation on pit wall	Vertical	Vertical	Vertical
Exposed surface area (m ²)	315,000 ¹	234,000 ¹	214,000 ¹
Sloping walls:			
-estimated %-age	35	35	35
-angle (degrees)	70	70	70
Exposed sulfur (g S/m ²)	48	64	144
Exposed CaCO ₃ (g/m ²)	225	100	25
Fracture surface (m ²) for each m ² of pit wall	20	40	40
Fracture flushed ² :			
-monthly	28%	28%	28%
-yearly	2%	2%	2%
-not during operation	70%	70%	70%

¹ Surface areas of any collapsed rock on benches are not included.

² Values for fracture flushing is based on calibration to existing pH data.

Because water levels in the saturated zone do not fluctuate greatly throughout the year, except probably during high recharge events in spring, a relatively constant saturated inflow was calculated (Table 5-2) based on pumpage rates during relatively dry months when precipitation would not contribute significantly to pumpage. Unsaturated flows in April were determined by assuming that flow (designated as yearly fracture flush) generally accounted for the difference between pit pumpage and the sum of snowmelt and saturated

flow. During winter months, unsaturated flow was considered to be negligible at an arbitrary value of 100 m³/month. During summer months, a monthly flow of about 3000 appeared reasonable based on the water balance. The monthly unsaturated flows were partitioned among the three rock units, as required by MINEWALL, on the basis of surface area.

The column entitled, "Required Balance", in Table 5-2 represents the monthly volume that must be added or subtracted from the sum of flows in order to obtain the monthly pumping rate. This column is not used in the modelling and simply reflects the error of estimation caused by such factors as (1) the choice of rounded, monthly constant values for saturated and unsaturated flows, (2) the use of one year of pumpage and precipitation data to obtain average monthly volumes, (3) surface runoff into the pit from the surrounding land surface, (4) evaporation and (5) snow removal. In general, most negative values in this column occur in summer, possibly reflecting evaporation, and most positive values occur in winter. In any case, the water balance in Table 5-2 is considered only generally suggestive of actual flows in the Main Zone and field measurements would be necessary to refine the balance. Any major discrepancies between Table 5-2 and actual flows would weaken the accuracy of the following predictions.

TABLE 5-2
Water Balance in the Main Zone Pit

Month ¹	Precip (mm) Onto Walls	in m ³ /month				
		Precip Onto Pit Bottom	Sat Flow	Unsat Flow	Required Balance ²	Pit Pumpage
Jan	0.0	300	25000	100	+ 2100	27,500
Feb	0.0	60	25000	100	+ 5640	30,800
Mar	18.1	6400	30000	100	- 6800	29,700
Apr	32.3	11100	30000	20000	- 1100	60,000
May	40 ³	15000	25000	3000	-13000	30,000
Jun	56.1	21100	25000	3000	+ 400	49,500
Jul	71.1	26700	25000	3000	- 2100	52,600
Aug	108.4	40700	25000	3000	-27000	41,700
Sep	32.0	12000	25000	3000	- 1500	38,500
Oct	70.1	26300	25000	3000	-20900	33,400
Nov	4.8	1800	25000	3000	+ 9700	39,500 ⁴
Dec	9.3	350	25000	100	+11450	36,900 ⁴

¹ 1989 data except for November and December, 1988

² Balance = Pumpage-Unsat Flow-Sat Flow-Precipitation Into Pit

³ Precipitation data for May, 1989 and 1988, not reported; approximate value from 1987 substituted

⁴ 1988 pumpage data overestimates true pumpage due to recirculation

Based on chemical analyses (Table 4-1), the background alkalinity and sulfate of the groundwater in the saturated zone was set at 150 and 400 mg/L. Background alkalinity of

the unsaturated flow prior to reaching oxidizable fractures and pit walls was set at 150 mg/L to match the saturated-zone value.

For decommissioning, the final area of the pit bottom was estimated at 37,000 m³ at an anticipated elevation of 1120 meters above sea level. Average pit crest was determined to be 1320 m and the equilibrium water level was specified at 1282 m, based on previous work described in Section 4.1. Steady-state flow through the pit at equilibrium was specified as 10,000 m³/month based on the yearly average values for precipitation into the pit plus a reduced saturated flow, which is considered only a gross estimate of the flow. Estimated water storage vs. elevation was determined through simplified geometry of the pit:

<u>Elevation (m.a.s.l.)</u>	<u>Storage (m³)</u>
1120	0
1140	896,000
1160	2,000,000
1180	3,380,000
1200	5,060,000
1220	7,070,000
1240	9,500,000
1260	12,200,000
1280	15,300,000
1282 (equilibrium)	15,600,000

The filling of the pit was assumed to occur primarily through groundwater inflow. However, Equity will likely divert surface water into the pit to accelerate the flooding, which would affect the following predictions.

The preceding information on water storage as well as data in Tables 5-1 and 5-2 were entered into MINEWALL for detailed simulations of the Main Zone Pit during operation and decommissioning. The results of simulating 2.5 years of operation before initiation of flooding and decommissioning are depicted in Figure 5-5 (compare to measured pH in Figure 4-8). During operation, predicted pH varies from about 6.7 to greater than 7.5, in agreement with the measured data. During the initiation of flooding in Month 31, there is a predicted temporary decrease to a pH value of approximately 5.9 due to the initial flush of surfaces

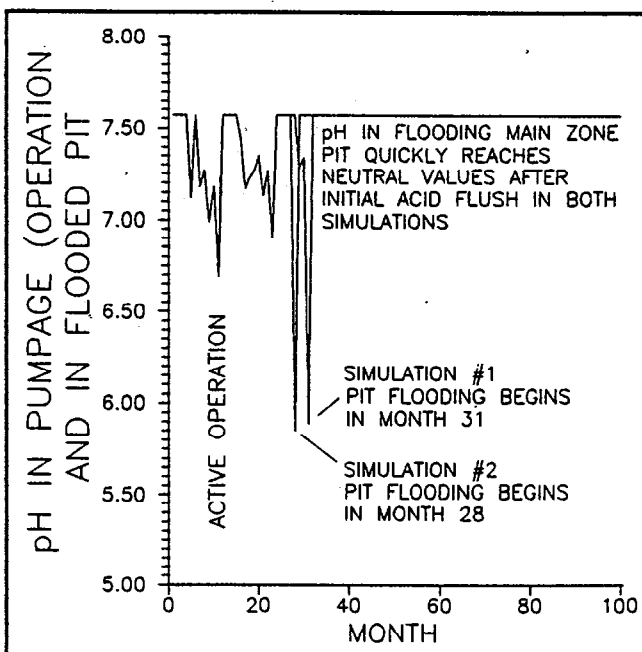


FIGURE 5-5. Best-fit Simulation of pH in the Main Zone Pit During Operation and Decommissioning.

which had been accumulating acid as well as a low volume of neutral-pH water in the pit. However, pH recovers quickly and remains at the maximum allowed pH in MINEWALL of 7.57. The simulation was extended to 300 years and the pH was found to remain at this value and, because of decreased rates of sulfide oxidation and consumption of sulfur, the pH is predicted to always remain at 7.57 after the initial acid flush. Figure 5-5 also illustrates the effect of initiating flooding during another month, Month 28 in this case during which the yearly flush of some fracture surfaces also occurs. This change in time of initial flooding results in a marginally lower pH in the initial flush, but pH again quickly recovers and then remains neutral.

Sulfate concentrations are known to be indicative of the rates of acid generation even when subsequent neutralization occurs. The sulfate trend corresponding to Figure 5-5 shows that saturated groundwater flow (with a background sulfate concentration of approximately 400 mg/L) is sometimes significantly diluted by precipitation and snowmelt (Figure 5-6), which would carry acidity to the pit pump and account for the corresponding decrease in pH. This fluctuation in sulfate has been measured in water pumped from the Main Zone Pit, although an apparently increasing background concentration distorts the seasonal trend (Figure 4-8).

As flooding begins, the initial acid flush into the pit water corresponds to a flush of sulfate of more than 500 mg/L, but concentrations in the pit water then decrease through increased water storage, less surface for acid generation, and decreasing rates of acid generation. The sulfate trend to 300 years (Figure 5-7) shows that sulfate concentrations begin to increase, probably as the result of sulfate accumulation in the pit water through time. The minor peaks in sulfate are apparently a modelling artifact from the discretization of pit storage and elevation. After the equilibrium water

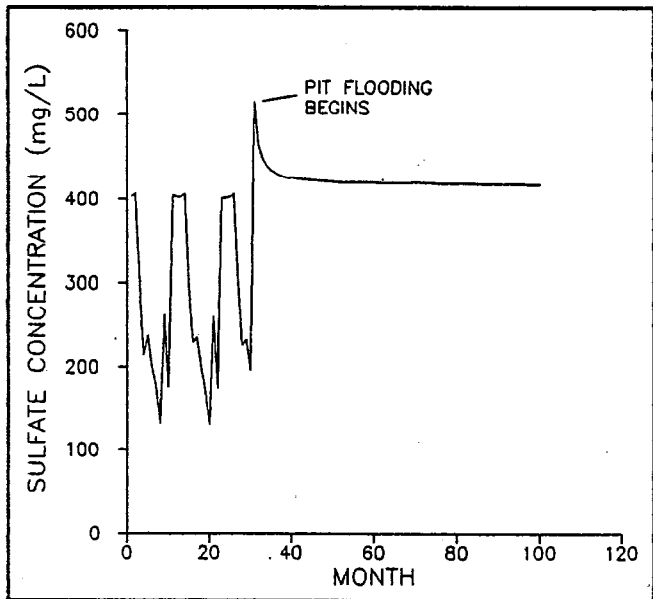


FIGURE 5-6. Best-fit Simulation of Sulfate in the Main Zone Pit.

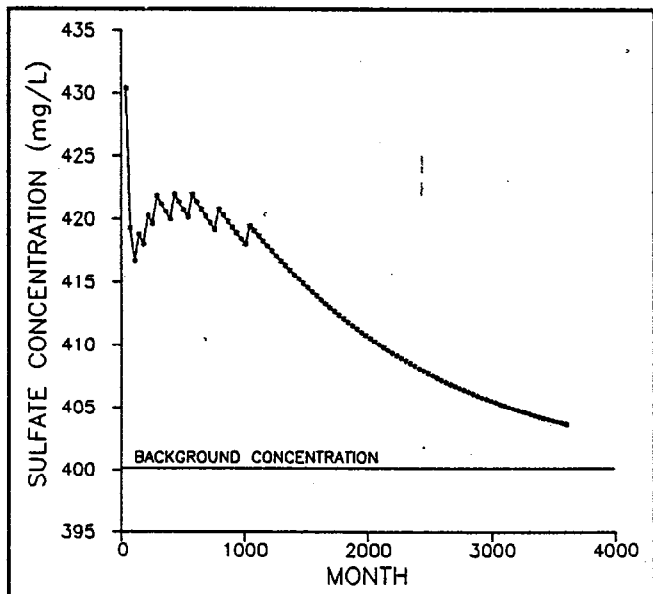


FIGURE 5-7. Predicted Sulfate Concentrations in the Main Zone Pit During Flooding.

level in the pit is attained, no new surfaces are flushed of accumulated acidity and sulfate is predicted to asymptotically approach the specified background concentration of 400 mg/L as flushing with background water occurs.

As mentioned earlier, the percentage of fracture surfaces which are flushed monthly, yearly, and not during operation are critical to predictions of water chemistry. These values can be determined through on-site forced fracture flushings or can be approximated through calibration to monthly values measured during operation. If areas of monthly or yearly flushed surfaces are overestimated, the simulated monthly values of pH will be lower than observed due to unrealistic flushing of acidity. Conversely, if the surfaces are underestimated, the monthly values of pH will be higher than observed.

Based on data from the Main Zone Pit, monthly values of pH in pumpage generally vary from about 6.8 to 8.2 with one low value of 6.5 in November of 1986, indicating a variable, but minor, degree of acid flushing throughout the year. The best-fit scenario with 28% of surfaces flushed monthly, 2% yearly, and 70% not during operation (Scenario #1, Figure 5-8 or Figure 5-5) was found to simulate well the observed range of pH. Scenario #2 with 20% flushed monthly, 5% yearly, and 75% not during operation yielded an unrealistically minor fluctuation in pH during operation. Scenario #3 with 35% flushed monthly, 10% yearly, and 55% not during operation yielded unrealistically low values of pH to approximately 3.9.

Based on this calibration to pH values during operation, Scenario #1 is determined to have the best-fit values of fracture flushing and thus should be the best predictor of pH during decommissioning. MINEWALL predicts

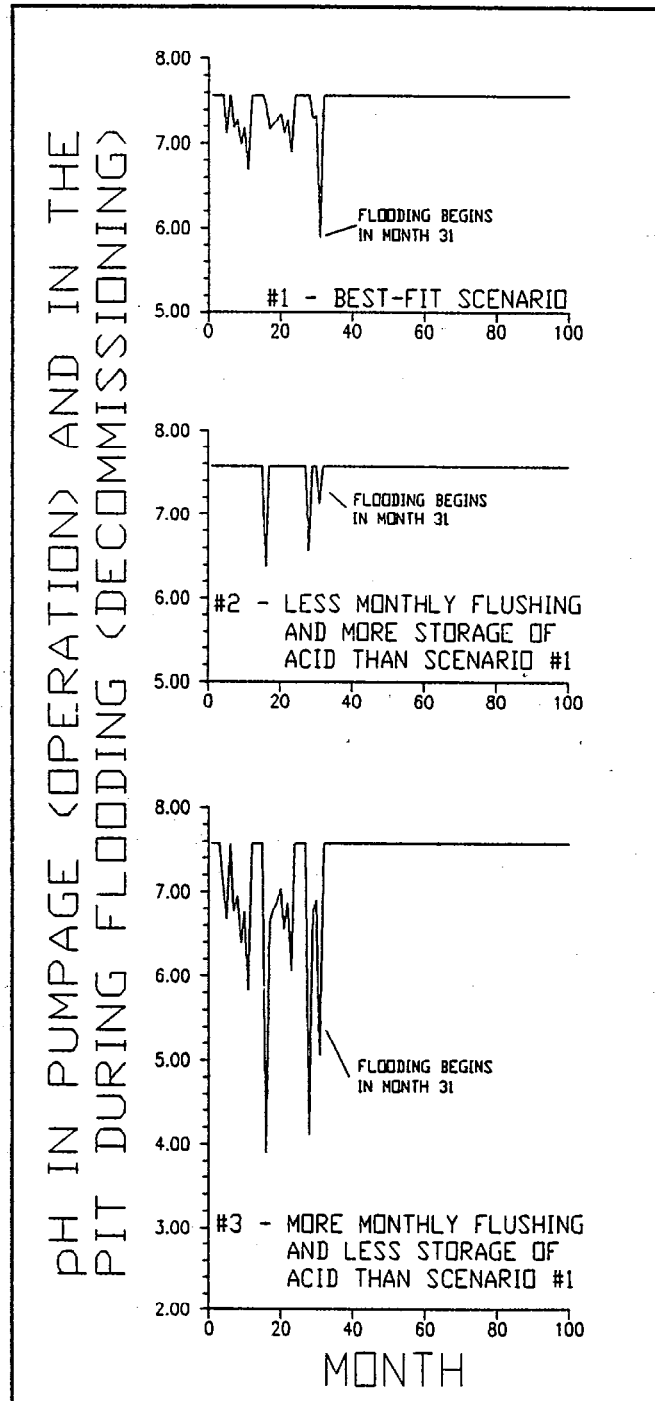


FIGURE 5-8. Simulations of pH in the Main Zone Pit With Alternative Values for Fracture Flushing.

the initial acid flush with a quick return to maximum allowed pH of 7.57 (Figure 5-5 and 5-8). It is important to note that all three scenarios have different pH values for the initial flush, but all return to neutral pH, indicating that, in the long-term, fracture flushing of accumulated acidity is not critical over the range of values examined here for the Main Zone Pit.

The current version of MINEWALL simulates metal leaching as simply a function of pH (Section 5.1.2). Because most of the predictions have indicated the maintenance of neutral-pH conditions, MINEWALL predicts metal levels at minimal levels (Figure 5-2 through 5-4). However, these metal concentrations at neutral pH are significantly affected by other factors such as aqueous complexation. Consequently, the predicted concentrations are not accurate and are not worthy of detailed discussion. Further work is required before metal leaching can be simulated and predicted (Section 6.1.1).

In conclusion, MINEWALL has been applied to the Main Zone Pit using measured and estimated data. Calibration of fracture flushing to existing operational values of pH have provided a best-fit scenario. Based on this scenario, this current version of MINEWALL predicts the Main Zone Pit to remain non-acidic throughout decommissioning, except for an initial acid flush at the beginning of flooding. Validation of MINEWALL and refinement of input data would improve the accuracy of these conclusions.

6. RECOMMENDATIONS

The final objective of this study is to formulate recommendations for further site-specific and general studies as well as recommendations for draft criteria of pit abandonment. These recommendations are based on the results of the preceding literature review, field examination, and computer simulations.

6.1 Recommended Further Studies

6.1.1 Site-Specific Recommendations

Based on the literature review and contacts with researchers (Section 3), Equity Silver Mines Ltd. has performed the most detailed assessment of potential for acid drainage in an open pit. The extent of this assessment has allowed the detailed simulations presented in Section 5. The following recommendations are not explicit criticisms of the existing information, but suggestions for improving the reliability of site-specific predictions for decommissioning.

- #1. Equity Silver Mines Ltd. apparently terminated the analyses for acidity, sulfate, and alkalinity from the Main Zone in April of 1989. These analyses should be re-started because they are key parameters in monitoring and predicting acid drainage. Anticipated costs are less than \$1000-\$2000 yearly.
- #2. Critical information on groundwater flow such as saturated flow, final equilibrium water level, and steady-state flow at equilibrium are only preliminary estimates. Detailed computer simulations, possibly requiring additional drilling and piezometer installation, are necessary for more accurate predictions. Anticipated costs are on the order of \$15,000 (no drilling) to \$150,000 (extensive drilling).
- #3. Unsaturated flows have been estimated on the basis of a water balance. Direct measurements of these flows would be valuable for more accurate assessments because this water is the primary mode of transport of acidity into the pit. Measurements of background alkalinity in this water would allow a refinement in the predictions of acid neutralization by enhancing the amount of neutralization allowed in the simulations. Anticipated costs are uncertain due to the technical complexity and lack of similar studies.
- #4. Measurements of acid generation at the Wall Stations (Appendix B) should be repeated periodically to determine seasonal variations and the anticipated general decay of the rates. Anticipated costs are less than \$2000 for each sampling session.
- #5. The extent of oxidizable fracture surfaces and the frequency of flushing of various surfaces are critical parameters in predicting water chemistry during both operation and decommissioning. Field examinations would require excavation and localized pressure-injection and capture tests. Anticipated costs are on the order of \$20,000-\$100,000.

- #6. The extensive acid-base accounting performed by Equity Silver Mines has been valuable in identifying geochemically distinct rock units and in calculating average values of exposed sulfide and neutralization capacity. However, not all neutralization capacity is equivalent to calcium-based carbonate minerals, although acid-base accounting implicitly includes this assumption. For more reliable predictions of pH neutralization and consumption of neutralization capacity, selected mineralogical analyses should be performed. Anticipated costs are less than \$4000.
- #7. The storage capacity of the pit at various elevations has been estimated in this study using a simplified geometry and assuming the storage capacity of the surrounding rock is nil. Equity Silver Mines should undertake a more detailed assessment of this information and include the storage capacity of the rock based on the hydrogeologic simulations of water-table drawdown (#2 above). This would be an internal task for the company.
- #8. Metal leaching is a complex process representing a combination of several independent mechanisms, resulting in site-specific and even small-scale variations. Due to the influence of factors other than pH in the Main Zone, Equity Silver Mines should undertake a more detailed assessment of metal leaching. This is critical for decommissioning, because water at neutral pH, but with toxic metal concentrations, remains an environmental problem. Anticipated costs vary from \$20,000 to more than \$70,000 depending on the length, number, and complexity of the experiments.

6.1.2 General Recommendations

The following recommendations are directed towards regulatory and research agencies in order to improve the prediction of impacts of operational or decommissioning phases in pits. These predictions are valuable tools during pre-phase investigations and decision making.

- #1. Current assessments and predictions of potential acid drainage are based on acid-base accounting and kinetic tests such as humidity cells. These techniques have been proven to be generally successful, but suffer from specific limitations. The government/industry MEND Program and the B.C. Acid Mine Drainage Task Force have sponsored studies which examined some of the limitations of the techniques and these studies should continue.

Terms of reference for examining the limitations of acid-base accounting should include mineralogy, alternative oxidants, solid-liquid interactions, and aqueous complexation. Anticipated costs are on the order of \$5,000. Terms of reference and costs for examining the limitations of kinetic tests should be based on the results of earlier investigations.

- #2. This study has concentrated on open pits with detailed data from only one pit. Studies of several more pits are required before the conceptual models and MINEWALL can be considered more widely applicable.

The terms of reference for additional studies of pits would include all of the parameters discussed in Section 5. A case study of a pit in sufficient detail for a rudimentary use of the models and MINEWALL would probably cost around \$10,000 to \$50,000. A more detailed study for reasonably confident, accurate predictions would cost significantly more.

- #3. This study has addressed acid drainage from mine walls, which includes underground mines by implication. Based on the framework developed here, underground mines can be brought into the models and MINEWALL with little difficulty.

The terms of reference would be to examine underground mines in light of this report and to indicate where additional details must be added to the models and MINEWALL. The anticipated cost for this inclusion of underground mines, including a literature review, is probably around \$5,000-\$15,000.

- #4. The current version of MINEWALL (v. 1.0) contains a number of simplifications which can affect the reliability of the simulations. The simplifications which are of greatest concern at this time are: (1) the rate of oxidation within internal fractures is independent of depth and oxygen diffusion, which can lead to an overestimation of the overall rate, (2) the rate of oxidation decreases as an arbitrary function of elapsed time which may overestimate the rate in the long term, (3) the rate of pit flooding decreases as an arbitrary function of original inflow, which can overestimate or underestimate actual inflow and the time to water-level equilibrium, and (4) pH and metal concentrations are predicted only on the basis of data from Equity's two pits, but should be more widely predicted on the basis of a speciation routine.

The terms of reference for the improvement of MINEWALL would include the elimination of the aforementioned simplifications by offering the option of inputting site-specific data or defaulting to prescribed equations such as those in Section 5.1.2. The anticipated costs are approximately \$1,000-\$4,000 for each simplification, including creation of code and preliminary testing.

- #5. MINEWALL has not been subjected to rigorous testing and verification. Additionally, full documentation is not available. If MINEWALL is to be used as a general tool with acceptable confidence in its applicability and predictions, these tasks must be performed. Testing and verification should include artificial data sets as well as realistic data sets based on measured data as much as possible. The degree of testing and verification is a function of the number of data sets simulated by the code, with confidence increasing as more simulations are performed and found accurate.

The terms of reference for this task should include the testing and verification of the MINEWALL code. Anticipated costs are on the order of \$5,000 to \$30,000 depending on the number of data sets and simulations.

6.2 Draft Criteria for Pit Decommissioning

As part of regulatory enforcement and mining code of practice, a list of criteria for decommissioning open pits would be valuable. In order to meet this need, the following list of criteria has been created by Morwijk Enterprises Ltd. as specified in the terms of reference for this study. The criteria are based on the results of this study and experience. These criteria are preliminary in nature and do not necessarily reflect the views of Equity Silver Mines Ltd., the mining industry, or federal and provincial regulatory agencies.

Proper planning for pit decommissioning must begin by detailed investigations prior to mining. Because the eventual state of the minesite following mining should resemble the pre-mining state to some degree, the pre-mining environment must be thoroughly characterized. Most Stage I Reports in British Columbia appear to define baseline conditions in adequate detail for most environmental systems, with the common exception of the groundwater. Failure to properly characterize the groundwater system will preclude the most reliable estimates of (1) variations in groundwater flows, water levels, and lateral extent of drawdown throughout operation and (2) groundwater flows and water levels during and after flooding. In other words, predictions for decommissioning at an operating pit with insufficient pre-mining information will have a higher degree of uncertainty. For these reasons most of the following criteria specifically address groundwater. Most of the criteria are found under Pre-mining, again demonstrating the importance of this early information.

6.2.1 Criteria for Pre-mining Investigations of Open Pits

- #1. Drilling and logging of core are critical in defining the detailed stratigraphy and geology (including fracture characteristics) of the rock within 1 km of the pit walls. The mining company must understand that this drilling must emphasize the waste rock as well as the ore rock.
- #2. High-integrity monitor wells and piezometers are required to allow periodic (1) measurements of hydraulic conductivity, (2) measurements of water levels, and (3) measurements of water chemistry. These wells should be located and installed by qualified hydrogeologists rather than geotechnical engineers and drillers (the Province of British Columbia is currently considering the legal licensing of hydrogeologists). The wells should be located in lines perpendicular to the mine walls unless the evaluation of geology suggests an alternative orientation.
- #3. Selected samples from the rock and sediment samples must be submitted for mineralogical analyses, particularly of sulfur-bearing minerals and neutralizing minerals, and for acid-base accounting. The Draft Acid Rock Drainage Technical Guide offers suggestions on sampling procedures and sampling size and number.

- #4. Selected samples must be submitted for kinetic tests. These tests are also discussed in detail in the AMD Guide.
- #5. In the wells and piezometers, the water levels and water samples should be collected every month for at least 1 year prior to mining. Additional monitoring time would indicate whether the measured data over 1 year are typical and average, but might cause a delay in mining.
- #6. Measurements of hydraulic conductivity in various rock units should be conducted with packer tests during drilling and with single-well or pump tests after piezometer installation. The single-well or pump tests should be repeated every 6 months due to settlement of the rock, well, and backfill after drilling. Dye tests would identify specific pathways of groundwater migration in the rock and would indicate the influence of exploratory drill holes on the overall water movement in the area.
- #7. Water samples should be collected every 4 months to determine baseline water chemistry and seasonal fluctuations in the chemistry. Groundwater chemistry is often more complex and more easily disturbed during sampling than surface-water chemistry, thereby requiring special sampling and handling protocols. Qualified hydrogeologists, rather than hydrologists and engineers, should design the appropriate sampling procedures based on the geology and geochemistry.
- #8. All of the hydrogeologic, hydrologic (surface-water), and climatic data should be entered into a computer program for initial simulations of water movement during operation and decommissioning. The predicted data for operation will be valuable to geotechnical engineers in evaluating the potential for wall instability. Water chemistry predictions should be made using a model such as MINEWALL which incorporates elements of water movement, acid-base accounting, and kinetic tests.

6.2.2 Criteria During Operation

- #1. The pumpage rates from the pit and the water chemistry of the pumped water must be monitored monthly. This provides for environmental protection and establishes a database for modelling calibration and predictions.
- #2. Water levels in all wells and piezometers must be monitored monthly to assist in modelling calibrations and predictions.
- #3. Wall Stations (such as those described in Appendix B) should be established around the pit perimeter and at various elevations to monitor temporal changes in the rates of acid generation and neutralization. This is of significant value to a mining company as the demonstration of rapidly decreasing rates of acid generation could lead to predictions of significantly improved predictions of water chemistry in the future.

- #4. Acid-base accounting samples should be collected on all benches around the pit perimeter. The number of samples from each bench should reflect the homogeneity of the exposed rock units. In homogeneous rock, a composite over a bench length of 10-30 meters appears acceptable. Nevertheless, the greater the number of samples, the greater the reliability of predictions.
- #5. All data gathered during operation should be periodically checked against predictions of the flow and chemistry made in the Pre-mining phase. Any discrepancies must be examined and accounted for, and the models must then be adjusted to improve predictions of later operation and eventual decommissioning.
- #6. On-site data and predictions should be periodically published in conference proceedings or journals for the benefit of the mining and environmental industries.

6.2.3 Criteria for Decommissioning

- #1. By following the criteria for the preceding two phases, there should be no major discrepancies from predictions during decommissioning. Any significant discrepancies signify oversights or errors and have two major implications: (1) all predictions of decommissioning flows and chemistry become questionable and (2) the mining company may have to incur significant costs to redesign the decommissioning plans and correct an environmentally poor situation. Treatment and handling costs for a pit full of acid or metal-laden water will exceed the costs for an environmentally acceptable decommissioning plan.
- #2. Water levels and chemistry in the pit and in all piezometers and wells must be monitored monthly for at least the first two years after decommissioning begins. Any significant discrepancies from predicted data should be treated as an emergency situation with rapid analysis, re-interpretation, and adjustment of decommissioning plans.
- #3. On-site data and predictions should be periodically published in conference proceedings or journals for the benefit of the mining and environmental industries.

7. SUMMARY

The first objective of this study was to evaluate available literature for relevant information on water movement and chemistry on and within mine walls. To provide a framework for evaluating the literature, conceptual models were developed, indicating the three important modes of water movement as (1) precipitation onto mine walls, (2) groundwater flow through the saturated zone into the base of the pit, and (3) groundwater flow through unsaturated fractures above the saturated zone. Precipitation onto mine walls is dependent on local climatic conditions and affected by factors such as ice coatings on the walls which isolates the wall from precipitation. For saturated groundwater flow, available literature indicated that open pits could affect water levels and groundwater movement for distances of several kilometers from the mine. Variations in hydraulic conductivity of subsurface materials, which can also affect groundwater flow, were reportedly limited to a small area around the mine with little effect on larger-scale groundwater movement. Only reports from Ohio State University were found to address unsaturated flow through fractures near mine walls, despite the major importance of these fractures on the severity of acid drainage.

In addition to water movement, the literature review also concentrated on acid generation and neutralization. Most of the available literature addressed acid generation in underground coal mines. A conceptual model of acid generation developed for this study highlighted the difference between acid generation in coal mines, which have porous sediments that allow acid generation to develop within the sediments, and in most "hard rock" mines in British Columbia where blocks of rock formed by fractures only allow acid generation on exposed surfaces. The implication of this difference is that there will be less acid generation from one kilogram of relatively impermeable rock than from one kilogram of porous rock. This was confirmed through comparisons of rates from coal mines and hard-rock mines in British Columbia.

During pit decommissioning, when a pit with exposed sulfide minerals is allowed to flood, the available literature indicated a common potential for the water within a flooding pit to become acidic. Detailed research indicated that the acidic conditions were at least partially attributable to unsaturated fractures that accumulated acidity until submerged. The lack of information on water movement and acid generation in fractures within mine walls is a major weakness in the current understanding of acid drainage from pits and underground workings.

A second objective of this study was to re-evaluate existing data at Equity Silver Mines and to perform a field study to determine time-dependent rates of acid generation and neutralization on exposed pit walls. The major focus was the Main Zone Pit, although information from the now-flooded Southern Tail Pit was found to be valuable to the study. The field study indicated that the average rate of acid generation from the walls was $11.0 \text{ mg SO}_4/\text{day}/\text{m}^2$, which was in agreement with the lower rates from coal mines and with rates from rock at the Cinola Gold Project in British Columbia. Contour diagrams of acid-base accounting parameters through the pit highlighted areas where acid generation is currently creating acidic conditions and iron staining and other areas where neutralizing minerals are maintaining neutral conditions. The pH values of water pumped from the

Main Zone Pit indicated that neutralization is successfully regulating all generated acidity at this time. Metal leaching within the Main Zone Pit can be significant, but within a wide range of pH around neutral values is independent of pH. As a result, metal leaching is strongly dependent on aqueous speciation and mineral solubility which cannot be evaluated with existing data.

The third objective of this study was to create a computer code to simulate the Main Zone Pit and other pits during operation and decommissioning. This code, named MINEWALL, was written in standard Fortran and has undergone preliminary verification. Nevertheless, the code is rudimentary at this time and not ready for general use.

MINEWALL was applied to the Main Zone Pit during operation by using site-specific information such as the number of distinct rock units in the pit, the rate of oxidation, the exposed quantity of sulfide and neutralizing minerals, the extent of internal fracturing, and the frequency of fracture flushing. Most of the requested information was obtained from maps, acid-base accounting, and field observations. The flushing frequency was unknown, but reasonably estimated through calibration of the frequencies to measured pH from the Main Zone since mining began.

As soon as the operational phase of the Main Zone was acceptably simulated by MINEWALL, the decommissioning phase was examined. The simulations indicated that the pH of the water accumulating in the Main Zone Pit during flooding would initially be mildly acidic then be quickly neutralized as the pit filled. The pit water was then predicted to remain neutral. These predictions were found to be applicable over a significant range of stored acidity within the pit walls. Metal leaching could not be reliably predicted because the neutral values of pH were within the range where more complex, currently undefined, mechanisms such as aqueous complexation regulate metal concentrations. Because MINEWALL has not been thoroughly tested and validated, the aforementioned predictions by MINEWALL include an unknown degree of uncertainty and error.

The fourth and last objective of this study was to formulate recommendations for both future studies and general draft criteria of pit decommissioning. The recommendations for future studies were divided into site-specific aspects for improving the reliability of the MINEWALL predictions of the Main Zone Pit and general aspects for improving the understanding of the critical processes that regulate water chemistry during open-pit operation and decommissioning. The recommendations for draft criteria of pit abandonment emphasized the importance of detailed baseline studies of groundwater prior to mining. The predictions for operation and decommissioning based on the pre-mining data should be periodically updated to maintain validity. By the time an operational phase is concluded, detailed predictions with a high degree of reliability should be in place to avoid an expensive revision of plans during decommissioning and the expensive treatment and handling of an environmental problem such as a pit filled with acid water. The draft criteria were developed by Morwijk Enterprises Ltd. and do not necessarily reflect the views of Equity Silver Mines Ltd., the mining industry, or federal and provincial regulatory agencies.

8. ACKNOWLEDGEMENTS

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APPENDIX A
DETAILS OF THE LITERATURE REVIEW

A1. KEYWORDS AND DATABASES FOR THE LITERATURE REVIEW

Keywords

Primary: Acid mine drainage
 Metal Leaching
 Acid
 Drainage
 Leaching
 Environment
 Water
 Groundwater

Limiting: Mine(s)
 or
 Mining
 and
 Wall(s)
 Roof(s)
 Floor(s)

Databases

Dialog Databases:

Aquaculture

CA Abstracts
 Chemical Engineering Abstracts
 Compendex Plus
 Current Technical Index
 Engineering Materials Abstracts
 Enviroline
 Environmental Bibliographies
 Federal [U.S.] Research In Progress
 Geoarchive
 Geobase
 Georef
 GPO Monthly Catalog
 Metadex
 National Technical Information Service
 Nonferrous Metals Abstracts
 Pollution Abstracts
 Scisearch
 Soviet Science & Technology
 Water Resources Abstracts
 Waternet
 World Aluminum Abstracts

QL Databases:

Canadian Environmental
 Mining Technology

CANOLE Databases:

Coal

APPENDIX B

**DETAILS OF THE WALL STATIONS FOR DETERMINING RATES
OF ACID GENERATION AND METAL LEACHING/
CHEMICAL ANALYSES OF FRESHET SEEPS**

B1. WALL STATIONS**STATION 1**

Location: Main Zone Pit, face of boulder resting on the south side of the 1320-meter bench. See Figure 4-9. Initial exposure around 1984.

Geologic Description: the boulder is part of a 15 m³ collapse from the south wall above the 1320 bench. The rock is gray quartzite (welded tuff?) with extensive sub-conchoidal microfractures, similar to rock in several locations on the south side of this bench. Depth of oxidation is less than 1 mm in the rock mass and greater than 1 meter in the fractures based on examination of the adjacent boulders. Despite the gray appearance of the rock mass, the bulk rock has a reddish-brown color due to apparently ancient oxidation of sulfide minerals exposed on the microfractures. A 2-cm wide weathered band of sulfide is exposed on the face of the boulder.

Isolated surface area: as a flat surface, 0.073 m²; including surface irregularities, possibly 10% greater.

Initial rinse: 800 mL was required to obtain a 500 mL sample; some suspended solids and rock particles were flushed from the area; field pH=4.9. See Table B1.

STATION 2

Location: Southern Tail Pit, upper portion of the eastern wall, will probably be covered with waste rock by January, 1990. See Figure 4-1. Initial exposure around 1980.

Geologic Description: this portion of the wall has a strike of N2°E (relative to true north) with a dip of 52°NW and is an exposed fracture plane with obvious iron staining and apparently significant bulk porosity. The rock mass is a light gray tuff and the bulk rock is reddish-brown from oxidation. Depth of oxidation in the rock mass is generally less than 1 mm, but up to 1 cm was noted. Based on an small-scale excavation of fractures, fracture oxidation was greater than 27 cm. The excavation revealed a series of 5 fracture planes within 27 cm parallel to the wall, all of which had recently oxidized. The fracture plane at 23 cm was generally dry whereas the plane at 27 cm was moist. Fractures perpendicular to the wall had apertures greater than 1 mm, but only to depths of a few mm.

Isolated surface area: as a flat plane, 0.602 m²; including surface irregularities, possibly 2% greater.

Initial rinse: 1100 mL were required to obtain a 500 mL sample; the powdery, porous surface absorbed over half the water; high suspended solids were flushed from the wall but settled within 1 hour; field pH=5.2. See Table B1.

STATION 3

Location: Main Zone Pit, on the southern wall just above the 1260-meter bench. See Figure 4-9. Initial exposure around 1985.

Geologic Description: this localized portion of the wall has a strike of N18°E with a dip of 80°SE, that is, the wall is overhanging so that precipitation does not frequently fall onto it. The surface is covered with rock dust due to infrequent flushing. The rock mass is an unidentified volcanic with no prominent fractures. Based on a nearby excavation, depth of oxidation is less than 1 mm in the rock mass. Oxidation in the fractures decreased within 20 cm of the wall, but was locally significant to >35 cm. Fracture aperture was approximately 5 mm at a depth of 1 cm and fracture height exceeded 40 cm. There were no apparent sulfide minerals.

Isolated surface area: as a flat plane, 0.483 m²; surface irregularities were minor.

Initial rinse: 800 mL were required to obtain a 500 mL sample; water had high suspended solids from the rock dust, which settled within 1 hour; field pH=6.1. See Table B1.

STATION 4

Location: Main Zone Pit, east wall just above the 1260-meter bench. See Figure 4-9. Initial exposure around 1985.

Geologic Description: the wall has a strike of N3°W and a dip of 72°SW. This portion of the wall is an exposed fracture plane. The rock is a dark, fine-grained, massive basic intrusive (fine gabbro?). There is minor disseminated sulfide minerals on the wall which occur in a disseminated manner or in veins. The sulfides show minor weathering. Depth of oxidation of the rock mass is less than 1 mm. Long (3-4 m), linear fractures cross at near-90° angles with apertures of around 1 mm. These fractures extend several tens of cm into the wall and appear to terminate at fracture planes parallel to the wall. Depth of oxidation in fractures is difficult to determine due to lack of consistent staining, but is at least tens of cm. Some fractures have basal iron trails from fracture flushing following oxidation.

Isolated surface area: as a flat plane, 0.138 m²; there is little surface irregularity and no significant fractures in the isolated area.

Initial rinse: 700 mL were required to obtain a 500 mL sample; water had no significant suspended solids; field pH=5.0. See Table B1.

STATION 5

Location: Main Zone Pit, the north wall on the run-away lane near the 1270-meter bench.
See Figure 4-9. Initial exposure around 1987.

Geologic Description: the wall has a strike of approximately N20°E with a dip of approximately 50°SE. The rock mass consists of massive volcanics with minor disseminated sulfide minerals. The rock has a reddish-brown color throughout apparently due to ancient oxidation. Fractures are conchoidal with depths of a few mm. Depths of oxidation from recent exposure are difficult to determine because of the prevalent, pre-existing oxidation.

Isolated surface area: as a flat plane, 0.079 m²; surface irregularities are minor.

Initial rinse: 600 mL were required to obtain a 500 mL sample; no suspended solids were noted; field pH=6.0. See Table B1.

TABLE B1
Water Analyses of the Initial Rinses¹

	S T A T I O N					
	No. 1	No. 2	No. 3	No. 4	No. 5	BLANK
Field pH	4.9	5.2	6.1	5.0	6.0	7.4
Lab pH	5.3	5.5	7.2	5.6	6.8	5.9
<u>as mg/L:</u>						
Acidity (as CaCO ₃)	9	14	4	5	3	<1
Alkalinity (CaCO ₃)	4.4	12.1	26.4	2.2	13.2	2.2
Sulfate	8.3	280	594	15.2	24.0	<1
Nitrate	0.055	0.11	3.5	0.035	0.15	0.010
<u>as ug/L (dissolved):</u>						
Aluminum	22	18	32	23	13	21
Antimony	2.4	0.7	12	8.3	2.2	0.5
Arsenic	0.3	0.3	0.2	0.1	0.2	<0.1
Cadmium	0.7	1.3	36(?)	7.1	1.1	<0.2
Copper	10	12	36	740	6	<1
Iron	60	30	<30	30	<30	<30
Zinc	120	270	3080	1220	140	<5

¹ samples were collected, handled, and analyzed following standard procedures at Equity Silver Mines Ltd. The "Blank" sample was of the deionized water used to rinse the walls.

B2. FRESHET SEEPS

Equity Silver Mines Ltd. reported analyses of wall seeps which were flowing during spring snowmelt. These seeps were located on the east and southern walls of the Main Zone Pit on the 1260 bench (see Figure 4-9) and apparently consisted of water flowing over the wall rather than actual groundwater discharge from fracture networks. The results of the analyses are reproduced in Table B2.

TABLE B2
Chemical Analyses of Freshet Seeps

	<u>No. 1</u>	<u>No. 2</u>	<u>No. 3</u>	<u>No. 4</u>	<u>No. 5</u>	<u>No. 6</u>	<u>No. 7</u>	<u>No. 8</u>	<u>No. 9</u>
pH	8.0	8.0	8.0	7.9	8.0	8.0	6.3	3.0	2.8
<u>as mg/L:</u>									
Acidity	2	3	3	5	8	4	53	1760	2040
Sulfate	340	270	450	290	820	490	1300	3550	3670
<u>as ug/L¹:</u>									
Copper	10	10	10	10	10	10	260	13500	10000
Iron	50	10	20	20	130	20	920	116000	192000
Zinc	20	10	20	10	120	930	4020	34500	35400

¹ dissolved metals

APPENDIX C

**ACID-BASE ACCOUNTING OF MAIN ZONE SAMPLES
(EQUITY SILVER MINES LTD., DECOMMISSIONING AND CLOSURE
PLAN, 1988)**

C1. ACID-BASE ACCOUNTING AT SPECIFIC INTERVALS ALONG BENCHES USING EPA METHODS

Morwijk- selected Label ¹	Bench	Equity- selected Label	NP ²	MPA ²	pH	NNP ²
1	1360	1-2	25.40	3.75	7.78	+21.65
2	1360	2-3	10.20	14.38	7.23	-4.18
3	1360	3-4	5.12	6.25	7.23	-1.13
4	1360	4-5	7.95	25.31	6.67	-17.36
5	1340	1-2	10.44	18.75	7.13	-8.31
6	1340	2-3	11.27	14.06	7.50	-2.79
7	1340	3-4	9.32	13.13	7.75	-3.81
8	1340	4-5	6.96	7.19	7.30	-0.23
9	1340	5-6	0.27	5.63	6.55	-5.36
10	1340	6-7	0.76	13.43	5.79	-12.67
11	1340	7-8	26.68	33.75	6.46	-7.07
12	1340	8-9	16.80	17.50	6.39	-0.70
13	1340	9-10	16.50	41.88	7.75	-25.38
14	1340	11-12	32.19	14.38	8.48	+17.81
15	1340	12-13	77.81	30.00	8.45	+47.81
16	1340	13-14	5.07	24.69	8.58	-19.62
17	1340	14-15	31.66	21.56	8.70	+10.10
18	1340	15-16	39.03	14.06	8.38	+24.97
19	1340	17-18	4.54	17.81	7.04	-13.27
20	1340	18-19	4.15	41.88	6.84	-37.73
21	1340	19-20	9.70	25.31	7.46	-15.61
22	1340	20-21	2.38	28.44	6.37	-26.06
23	1340	21-22	3.19	40.00	5.78	-36.81
24	1320	1-2	1.71	15.94	8.54	-14.23
25	1320	2-3	47.81	21.56	8.59	+26.25
26	1320	3-4	78.97	29.38	8.63	+49.59
27	1320	4-5	87.68	38.44	8.76	+49.24
28	1320	5-6	62.52	11.25	8.79	+51.27
29	1320	6-7	60.52	16.56	8.52	+43.96
30	1320	7-8	94.80	32.50	8.45	+62.30
31	1320	8-9	1.08	54.69	8.45	-53.61
32	1320	9-10	24.66	40.00	8.42	-15.34
33	1320	10-11	9.95	68.75	7.85	-58.80
34	1320	11-12	9.32	50.63	6.90	-41.31
35	1320	12-13	19.22	30.63	8.14	-11.41
36	1320	13-14	11.30	75.63	7.35	-64.33
37	1320	14-15	5.35	130.44	7.67	-125.09
38	1320	15-16	11.03	106.88	7.53	-95.85
39	1320	16-17	5.39	81.56	6.88	-76.17
40	1320	17-18	0.81	52.50	5.12	-51.69
41	1320	18-19	1.71	44.38	4.90	-42.67
42	1320	19-20	0.36	70.94	4.90	-70.58
43	1320	21-22	38.07	36.56	7.68	+1.51

<u>Morwijk- selected Label¹</u>	<u>Bench</u>	<u>Equity- selected Label</u>	<u>NP²</u>	<u>MPA²</u>	<u>pH</u>	<u>NNP²</u>
44	1320	22-23	11.74	34.06	6.61	-22.32
45	1320	23-24	44.25	31.88	7.92	+12.37
46	1320	24-25	184.10	31.88	7.79	+152.22
47	1320	25-26	13.43	127.19	7.42	-113.76
48	1320	26-27	2.25	72.50	6.53	-70.25
49	1320	27-28	8.54	22.19	6.98	-13.65
50	1320	28-29	1.01	40.63	4.93	-39.62
51	1300	A-B	1.79	121.25	5.10	-119.46
52	1300	B-C	7.18	64.06	6.94	-56.88
53	1300	C-D	9.88	60.00	6.32	-50.12
54	1300	D-E	6.33	76.56	4.61	-70.23
55	1300	E-F	5.57	106.56	4.97	-100.99
56	1300	F-G	4.99	196.56	4.65	-191.57
57	1300	G-H	9.21	121.25	5.18	-112.04
58	1300	H-I	17.47	122.50	7.62	-105.03
59	1300	I-J	20.90	60.00	8.13	-39.10
60	1300	J-K	32.95	129.38	7.83	-96.43
61	1300	K-L	14.12	88.13	7.96	-74.01
62	1300	L-M	19.99	51.25	7.94	-31.26
63	1300	M-N	9.48	57.50	7.66	-48.02
64	1300	N-O	5.57	66.22	7.86	-60.65
65	1300	O-P	21.31	46.67	8.45	-25.36
66	1300	P-Q	41.95	48.68	8.35	-6.73
67	1300	Q-R	55.50	44.38	8.59	+11.12
68	1300	R-S	35.51	24.06	8.72	+11.45
69	1300	S-T	37.16	13.75	8.75	+23.41
70	1300	T-U	62.60	24.06	8.57	+38.54
71	1300	U-V	67.08	38.75	8.43	+28.33
72	1300	V-W	46.41	24.06	8.58	+22.35
73	1300	W-X	36.40	14.06	8.69	+22.34
74	1300	X-Y	37.16	21.88	8.60	+15.28
75	1300	Y-Z	22.46	41.88	8.36	-19.42
76	1300	Z-1	33.04	30.82	8.50	+2.22
77	1300	1-2	26.76	57.72	8.48	-30.96
78	1300	2-3	39.39	34.02	8.39	+5.37
79	1300	3-4	44.76	51.41	8.27	-6.65
80	1300	4-5	48.56	32.91	8.04	+15.65
81	1300	5-6	71.19	24.49	8.34	+46.70
82	1300	6-7	52.36	23.42	8.26	+28.94
83	1300	7-8	62.44	24.04	8.54	+38.40
84	1300	8-9	67.39	35.95	8.47	+31.44
85	1300	9-10	8.26	51.52	8.53	-43.26
86	1300	10-11	49.72	41.06	8.39	+8.66
87	1300	11-12	59.71	44.31	8.01	+15.40
88	1300	12-13	85.28	68.75	8.36	+16.53

<u>Morwijk- selected Label¹</u>	<u>Bench</u>	<u>Equity- selected Label</u>	<u>NP²</u>	<u>MPA²</u>	<u>pH</u>	<u>NNP²</u>
89	1300	13-14	58.80	97.19	7.93	-38.39
90	1300	14-15	43.61	75.00	8.06	-31.39
91	1300	15-16	33.53	48.44	8.20	-14.91
92	1300	16-17	57.32	25.31	8.05	+32.01
93	1300	17-18	7.70	38.75	6.49	-31.05
94	1300	18-19	5.73	51.88	6.66	-46.15
95	1300	19-20	4.58	28.44	6.59	-23.86
96	1300	20-21	0.27	29.06	6.53	-28.79
97	1300	21-22	10.29	42.19	7.01	-31.90
98	1300	22-23	11.54	226.90	6.07	-215.36
99	1300	23-24	0.40	59.38	4.32	-58.98
100	1280	1-2	34.68	71.25	8.26	-36.57
101	1280	2-3	42.62	27.19	8.33	+15.43
102	1280	3-4	53.53	25.00	8.42	+28.53
103	1280	4-5	3.98	46.25	7.73	-42.27
104	1280	5-6	5.43	60.00	7.14	-54.57
105	1280	6-7	6.29	28.13	7.73	-21.84
106	1280	7-8	2.38	45.31	7.53	-42.93
107	1280	8-9	19.76	37.50	8.02	-17.74
108	1280	9-10	9.66	39.69	8.09	-30.03
109	1280	10-11	14.94	86.25	8.24	-71.31
110	1280	11-12	10.51	133.44	7.43	-122.93
111	1280	12-13	0.40	110.94	4.83	-110.54
112	1280	13-14	6.63	106.88	6.10	-100.25
113	1280	14-15	15.27	82.81	7.46	-67.54
114	1280	15-16	21.72	49.38	7.38	-27.66
115	1280	16-17	32.11	23.75	7.05	+8.36
116	1280	17-18	9.25	28.75	6.52	-19.50
117	1280	18-19	13.03	19.69	6.32	-6.66
118	1280	20-21	19.92	37.50	8.39	-17.58
119	1280	21-22	81.37	33.44	8.56	+47.93
120	1280	22-23	76.72	39.69	8.63	+37.03
121	1280	23-24	40.02	42.19	8.67	-2.17
122	1280	24-25	55.58	63.44	8.27	-7.86
123	1280	25-26	27.12	45.00	8.35	-17.88
124	1280	26-27	26.88	62.19	8.19	-35.31
125	1280	27-28	17.92	71.25	8.23	-53.33
126	1280	28-29	15.31	50.31	8.37	-35.00
127	1280	29-30	9.43	60.00	8.23	-50.57
128	1280	30-31	5.57	81.88	7.95	-76.31
129	1280	31-32	5.57	160.31	7.69	-154.74
130	1280	32-33	27.58	75.63	8.04	-48.05
131	1280	33-34	11.16	87.81	7.49	-76.65
132	1280	34-35	5.73	89.38	7.04	-83.65
133	1280	35-36	13.59	69.06	6.42	-55.47

<u>Morwijk- selected Label¹</u>	<u>Bench</u>	<u>Equity- selected Label</u>	<u>NP²</u>	<u>MPA²</u>	<u>pH</u>	<u>NNP²</u>
134	1280	36-37	2.54	80.63	6.33	-78.09
135	1280	37-38	7.75	51.25	7.63	-43.50
136	1280	38-39	7.86	71.56	7.46	-63.70
137	1280	39-40	8.89	67.19	6.67	-58.30
138	1280	40-41	6.24	71.25	5.33	-65.01
139	1280	41-42	1.68	52.19	5.08	-50.51
140	1280	42-43	1.44	20.00	5.19	-18.56
141	1280	43-44	7.82	83.44	6.12	-75.62

C2. ACID-BASE ACCOUNTING OF SPECIFIC LITHOLOGIES (BENCH 1300)

<u>Morwijk- selected Label¹</u>	<u>Type</u>	<u>Equity- selected Label</u>	<u>NP²</u>	<u>MPA²</u>	<u>pH</u>	<u>NNP²</u>
142	ANDESITE	J-L	68.53	56.56	8.03	+11.97
60-61	BULK	J-L	23.54	108.76	7.90	-85.22
143	LAPILLI TUFF	O-P	1.53	11.25	7.94	-9.72
144	GABBRO	O-P	25.44	9.06	8.58	+16.38
145	ASH TUFF	O-P	19.45	51.88	8.46	-32.43
146	GABBRO	P	6.61	11.88	8.74	-5.27
65	BULK	O-P	21.31	46.67	8.45	-25.36
147	QTZ LATITE	W	18.96	20.00	8.64	-1.04
72	BULK	V-W	46.41	24.06	8.58	+22.35

C3. DUPLICATE ANALYSES BY BC RESEARCH METHOD

Morwijk- selected <u>Label</u> ¹	<u>Bench</u>	Equity- selected <u>Label</u>	<u>NP</u> ²	<u>MPA</u> ²	<u>NNP</u> ²
148	1300	A-B	5.44	118.65	-113.21
149	1300	B-C	8.58	62.69	-54.11
150	1300	C-D	8.97	58.71	-49.74
151	1300	D-E	5.00	74.92	-69.92
152	1300	E-F	2.75	104.28	-101.53
153	1300	F-G	3.14	192.35	-189.21
154	1300	G-H	5.79	118.65	-112.86
155	1300	H-I	19.71	119.87	-100.16
156	1300	I-J	26.97	58.71	-31.74
157	1300	J-K	37.66	126.60	-88.94
158	1300	K-L	13.93	86.24	-72.31
159	1300	J-L	23.54	55.35	-31.81

¹ a series of consecutive numbers was chosen for simplicity in labelling and use in Figure 4-10.

² units are tonnes of CaCO₃ equivalent / 1000 tonnes of rock

APPENDIX D

THE MINEWALL COMPUTER PROGRAM AND AN EXAMPLE SIMULATION

D1. The MINEWALL Computer Program

The computer program developed for the simulation of the Main Zone and other open pits has been named MINEWALL. The program is written in standard Fortran and has been successfully compiled with the Microsoft Optimizing Fortran Compiler v.4.0. Portions of the computer code have been visually rechecked and some variables have been monitored during trial executions in order to identify coding errors. Based on more than 40 trial executions, the code appears to be free of significant errors. However, validity of the results can only be confirmed through more extensive testing, verification, and documentation, which are beyond the objectives of this study.

The input data file for MINEWALL is in the form of a formatted ASCII file. The input file (e.g, Section D2) can be created by examining the READ statements in the INPT subroutine or, more conveniently, by executing the PREMINE preprocessor program.

Output from MINEWALL (e.g., Section D3) is directed to a file, named during execution by the user. The option is also offered to send selected results to a numeric-only ASCII file for import into spreadsheets and graphics programs.

```

COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
CHARACTER*64 FNAME1,FNAME2,FNAME3
C
C *****
C MINEWATER - A PROGRAM TO SIMULATE MINEWATER CHEMISTRY DURING
C OPERATION, FLOODING, AND DECOMMISSIONING
C
C WRITTEN BY KEVIN A. MORIN, MORWUK ENTERPRISES LTD., 11/89
C ** VERSION 1.0, 11/89 **
C
C FUNDING WAS PROVIDED BY THE CANADIAN/BRITISH COLUMBIA MINERAL
C DEVELOPMENT AGREEMENT UNDER THE DIRECTION OF THE
C CANADIAN DEPARTMENT OF ENERGY, MINES, AND RESOURCES AND
C THE BRITISH COLUMBIA MINISTRY OF ENERGY, MINES, AND
C PETROLEUM RESOURCES
C
C DIRECTION WAS PROVIDED BY EQUITY SILVER MINES LTD.
C *****
C
C
C ***** INITIALIZATION
C WRITE (*,1)
C 1 FORMAT (///)
C WRITE (*,'(A)') 'WHAT IS THE NAME OF THE INPUT DATA FILE?'
C READ (*,'(A)') FNAME1
C OPEN (5,FILE=FNAME1)
C WRITE (*,'(A)') 'WHAT DO YOU WANT TO CALL THE OUTPUT FILE?'
C READ (*,'(A)') FNAME2
C OPEN (6,FILE=FNAME2)
C WRITE (*,2)
C 2 FORMAT (///) 'DO YOU WANT A SEPARATE ASCII FILE WITHOUT LABELS/'
C * 'SUITABLE FOR IMPORT TO SPREADSHEETS AND GRAPHICS PROGRAMS?/'
C * 'ANSWER: 0 = NO OR 1 = YES'
C READ (*,3) IASC
C 3 FORMAT (I5)
C IF (IASC.EQ.1) THEN
C WRITE (*,'(A)') 'WHAT DO YOU WANT TO CALL THE ASCII FILE?'
C READ (*,'(A)') FNAME3

```

```

      OPEN (7,FILE=FNAME3)
      ENDIF
      WRITE (*,'(A)') 'HOW OFTEN DO YOU WANT OUTPUT: 1= EVERY MONTH'
      WRITE (*,'(A)') ' 2=EVERY SECOND MONTH, 12=EVERY YEAR, ETC.'
      READ (*,3) IOUT
      WRITE (*,4) IOUT
      4 FORMAT (// ' OUTPUT WILL BE SENT TO FILE(S) EVERY ',5,'MONTHS')
      CALL INPT
      CALL WATER
      DO 10 I=1,IRLNO
        TOTS(I)=TOTS(I)*3000.
        TSO(4,I)=0.0
        DO 20 J=IMFL+1,12
          20 TSO(4,I)=TSO(4,I)+RATE(I,J)
          YRAT(I)=0.0
          DO 30 J=1,12
            30 YRAT(I)=YRAT(I)+RATE(I,J)
            TSO(5,I)=FLOAT(ITOT)*YRAT(I)/12.
          10 CONTINUE
          DO 40 I=1,IRLNO
            TOK(2,I)=TOK(1,I)*OFT(1,1)*OFS(I)/100.
            TOK(3,I)=TOK(1,I)*OFT(1,2)*OFS(I)/100.
            TOK(4,I)=TOK(1,I)*OFT(1,3)*OFS(I)/100.
          40 CONTINUE
          IYR=0
          IMON=0
          PVOL=0.0
          NUFL=IRLNO
          IOTT=0
          IF (IFLD.EQ.0) IFLD=1000000
C
C
C ***** TIME LOOP *****
      DO 100 KTIM=1,ITIM
        IMON=IMON+1
        IF (IMON.EQ.13) THEN
          IYR=IYR+1
          IMON=1
          DO 101 KKT=1,IRLNO
            DO 102 KKT=1,12
              RATE(KKT,KKT)=RATE(KKT,KKT)*0.95
            102 CONTINUE
          101 CONTINUE
          ENDIF
          ITTT=0
          IOTT=IOTT+1
          IF (IOTT.EQ.IOUT) THEN
            ITTT=1
            IOTT=0
            ENDIF
          J=IMON
C
C ** ROCK-UNIT LOOP **
      DO 200 I=1,IRLNO
        CALL SULFUR(I,J)
        CALL ALK(I,J)
        200 CONTINUE
        IF (KTIM-IFLD) 500,300,400
        500 CALL OPER(I)
        IF (ITTT.EQ.1) CALL OUT1
        IF (IASC.EQ.1.AND.ITTT.EQ.1) CALL OUT3
        GO TO 100
        300 CALL PIT(I)
        400 CALL DECOM(I)
        IF (ITTT.EQ.1) CALL OUT2
        IF (IASC.EQ.1.AND.ITTT.EQ.1) CALL OUT4
        100 CONTINUE
        CLOSE (5)
        CLOSE (6)
        IF (IASC.EQ.1) CLOSE (7)
        STOP

```

```

END
C
C
C
SUBROUTINE WATER
C CALCULATES WALL WASH OVER EACH ROCK UNIT PER MONTH
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
DO 10 J=1,12
DO 20 I=1,IRLNO
20 RLFL(I,J)=RLHA(I)*PRHA(J)/1000.+(RLAR(I)-RLHA(I))*COS(RLGL(I))
**PRGL(J)/1000.
10 RLFL(IRLNO+1,J)=RLAR(IRLNO+1)*PRPB(J)/1000.
RETURN
END
C
C
SUBROUTINE SULFUR(I,J)
C CALCULATES SULFATE LEACHING AND TOTAL-SULFUR CONSUMPTION
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
TOTS(I)=TOTS(I)-RATE(I,J)
IF (TOTS(I).LT.0.0) THEN
RATE(I,J)=RATE(I,J)+TOTS(I)
DO 30 K=1,12
30 RATE(I,K)=0.0
ENDIF
TSO(1,I)=RATE(I,J)*RLAR(I)
IF (PRHA(J).EQ.0.0.AND.PRGL(J).EQ.0.0) TSO(1,I)=0.0
TSO(2,I)=RATE(I,J)*RLAR(I)*OFS(I)
TSO(3,I)=TSO(2,I)*OFT(I,1)/100.
TSO(4,I)=TSO(3,I)+TSO(2,I)*OFT(I,2)/100.
IF (J.EQ.IMFL) THEN
TSO(3,I)=TSO(3,I)+TSO(4,I)
TSO(4,I)=0.0
ENDIF
TSO(5,I)=TSO(5,I)+TSO(2,I)*OFT(I,3)/100.
RETURN
END
C
C
SUBROUTINE ALK(I,J)
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
TAL(1,I)=ALKS*GWST(I)*1000.
IF (TOK(1,I).NE.0.0) THEN
IF (RLFL(I,J).EQ.0.0) THEN
TAL(2,I)=0.0
GO TO 20
ENDIF
TAL(2,I)=TSO(1,I)/(RLFL(I,J)*1000.)
TAL(2,I)=(TAL(2,I)*200./96.)+50.)*RLFL(I,J)*1000.
TOK(1,I)=TOK(1,I)-TAL(2,I)/RLAR(I)

```

```

20 IF (TOK(1,I).LT.0.0) THEN
    TAL(2,I)=TAL(2,I)+TOK(1,I)*RLAR(I)
    TOK(1,I)=0.0
ENDIF
ELSE
    TAL(2,I)=0.0
ENDIF
TAL(3,I)=0.0
IF (TOK(2,I).EQ.0.0.AND.TOK(3,I).EQ.0.0) GO TO 100
AR1=RLAR(I)*OFS(I)*OFT(I,1)/100.
IF (GWUS(I,I).EQ.0.0) THEN
    TAL(3,I)=0.0
    GO TO 30
ENDIF
TAL(3,I)=TSO(3,I)/(GWUS(I,I)*1000.)
TAL(3,I)=((TAL(3,I)*200./96.)+50.)*GWUS(I,I)*1000.
30 IF (J.EQ.IMFL) THEN
    AR2=RLAR(I)*OFS(I)*OFT(I,2)/100.
    IF (AR1.EQ.0.0.AND.AR2.EQ.0.0) THEN
        AL1=0.0
        AL2=0.0
        FAC2=0.0
        FAC3=0.0
        GO TO 40
    ENDIF
    AL1=50.*GWUS(I,I)*1000./(AR1+AR2)
    AL2=TAL(3,I)-AL1
    RATT=YRAT(I)+RATE(I,I)
    FAC3=AL1*AR2/(AR1+AR2)+AL2*YRAT(I)/RATT
    FAC2=AL1*AR1/(AR1+AR2)+AL2*RATE(I,I)/RATT
40 IF (TOK(2,I).LT.0.0) THEN
    TALT=0.0
    FAC1=0.0
    FAC4=0.0
    IF (TOK(3,I).EQ.0.0) THEN
        FAC2=FAC2+FAC3
    ELSE
        FAC1=TOK(3,I)-FAC3
        FAC4=1.0
    ENDIF
    IF (FAC1.LT.0.0) THEN
        TALT=TOK(3,I)*AR2
        TOK(3,I)=0.0
        TARF=TALT
        IF (AR2.NE.0.0) TARF=TALT/AR2
        FAC2=FAC2+FAC3-TARF
    ELSE
        TALT=TALT+FAC3*AR2*FAC4
        TOK(3,I)=FAC1*FAC4
    ENDIF
    FAC1=0.0
    FAC3=0.0
    FAC4=0.0
    IF (TOK(2,I).EQ.0.0) THEN
        FAC3=FAC2
    ELSE
        FAC1=TOK(2,I)-FAC2
        FAC4=1.0
    ENDIF
    IF (FAC1.LT.0.0) THEN
        TALT=TALT+TOK(2,I)*AR1
        FAC3=FAC2-TOK(2,I)*AR1
        TOK(2,I)=0.0
    ELSE
        TALT=TALT+FAC2*AR1*FAC4
        TOK(2,I)=FAC1*FAC4
    ENDIF
    FAC1=0.0
    FAC4=0.0
    IF (FAC3.GT.0.0.AND.TOK(3,I).GT.0.0) THEN
        FAC1=TOK(3,I)-FAC3

```

```

      FAC4=1.0
      ENDIF
      IF (FAC1.LT.0.0) THEN
        TALT=TALT+TOK(3,I)*AR2
        TOK(3,I)=0.0
      ELSE
        TALT=TALT+FAC3*FAC4
        TOK(2,I)=FAC1*FAC4
      ENDIF
      TAL(3,I)=TALT
      ENDIF
    ELSE
      IF (AR1.EQ.0.0) THEN
        TARF=0.0
      ELSE
        TARF=TAL(3,I)/AR1
      ENDIF
      TOK(2,I)=TOK(2,I)-TARF
      ENDIF
      IF (TOK(2,I).LT.0.0) THEN
        TAL(3,I)=TAL(3,I)+TOK(2,I)*AR1
        TOK(2,I)=0.0
      ELSE
        TAL(3,I)=0.0
      ENDIF
    100 TAL(3,I)=TAL(3,I)+ALKU*GWUS(I,I)*1000.
      RETURN
    END

```

C
C

```

      SUBROUTINE OPER(J)
      COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
      *UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
      *PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
      *RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
      *IRLNO
      COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
      *PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
      *BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
      TALK=TAL(1,I)
      TSO4=0.0
      TOTF=GWST(J)
      DO 10 I=1,IRLNO
        TALK=TALK+TAL(2,I)+TAL(3,I)
        TSO4=TSO4+TSO(1,I)+TSO(3,I)
    10 TOTF=TOTF+RLFL(I,I)+GWUS(I,I)
      TOTF=TOTF+RLFL(IRLNO+1,I)
      TOTF=TOTF*1000.
      CSO4=TSO4/TOTF
      CACID=CSO4*200./96.
      CALK=TALK/TOTF
      CALL PHS
      CALL METAL
      CSO4=CSO4+BSOT*GWST(J)*1000./TOTF
      IF (XACID.GT.0.0) THEN
        CACID=CACID-CALK
        CALK=0.0
      ELSE
        CALK=CALK-CACID
        CACID=0.0
      ENDIF
      RETURN
    END

```

C
C

```

      SUBROUTINE PIT(J)
    C INITIALIZATION OF DECOM SCENARIO
      COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
      *UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
      *PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
      *RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),

```

```

*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
JJ=J-1
IF (JJ.EQ.0) THEN JJ=12
TOTF=0.0
DO 20 JK=1,12
DO 10 IK=1,IRLNO
TOTF=TOTF+RLFL(IK,JK)
10 GWUU(IK,JK)=GWUS(IK,JK)
20 TOTF=TOTF+RLFL(IRLNO+1,JK)
TOTF=TOTF/12.
RLAR(IRLNO+1)=0.0
RLHA(IRLNO+1)=0.0
DO 30 IK=1,IRLNO+1
RLMM(IK)=RLAR(IK)
30 RLNN(IK)=RLHA(IK)
PACID=CACID
PALK=CALK
PSO4=CSO4
PVOL=0.0
ELDIF=ELPW-ELPB
FLDIF=TOTF-GWEQ
AFLN=TOTF
ALEV=ELPB
WRITE (6,40)
40 FORMAT (///' **** DECOMMISSIONING BEGINS ****')
RETURN
END

```

C
C

```

SUBROUTINE DECOM(J)
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
JJ=J-1
IF (JJ.EQ.0) THEN JJ=12
PVOL=PVOL
PVOL=PVOL+AFLN
AFLO=AFLN
ALED=ALEV
DO 10 IK=1,50
K=IK
IF (PVOL.LT.PITC(K)) GO TO 20
IF (ELEV(K).EQ.(-1.0)) THEN
ALEV=ELEV(K-1)
PVOL=PITC(K-1)
AFLN=GWEQ
GO TO 30
ENDIF
10 CONTINUE
20 A=PITC(K)
B=PVOL-PITC(K-1)
C=ELEV(K)-ELEV(K-1)
ALEV=C*B/A+ELEV(K-1)
IF (ALEV.GT.ELPW) ALEV=ELPW
DIF=(ALEV-ELPB)/ELDIF
DIF=1.0/(10.**(DIF*DIF))
AFLN=(FLDIF*DIF)+GWEQ
IF (ALEV.EQ.ELPW) AFLN=GWEQ
30 TALK=ALKS*AFLO*1000.
TSO4=0.0
DO 100 I=1,IRLNO
CALL RAT(RAT1,RAT2,I)
TALK=TALK+TAL(2,I)+TAL(3,I)+RLMM(I)*TOK(4,I)*RAT1

```

```

TSO4=TSO4+TSO(1,I)+TSO(3,I)+TSO(5,I)*RAT1
RLAR(I)=RLMM(I)*RAT2
RLHA(I)=RLNN(I)*RAT2
DO 101 JK=1,12
101 GWUS(I,JK)=GWUU(I,JK)*RAT2
100 CONTINUE
PACP=PACID*PVOD*1000.+TSO4*200./96.
PSOP=PSO4*PVOD*1000.+TSO4+BSOT*AFLO*1000.
PALL=PALK*PVOD*1000.+TALK
VOL=PVOL*1000.
PACID=PACP/VOL
PSO4=PSOP/VOL
PALK=PALL/VOL
IF (ALEV.GT.ELPW-1) THEN
  FLOAD=PACID*GWEQ*1000.
  PACP=PACP-FLOAD
  PACID=PACP/VOL
  FLOAD=PSO4*GWEQ*1000.
  PSOP=PSOP-FLOAD
  PSO4=PSOP/VOL
  FLOAD=PALK*GWEQ*1000.
  PALL=PALL-FLOAD
  PALK=PALL/VOL
ENDIF
CACID=PACID
CSO4=PSO4
CALK=PALK
CALL PHS
CALL METAL
CALL WATER
IF (XACID.GT.0.0) THEN
  PACID=PACID-PALK
  PALK=0.0
ELSE
  PALK=PALK-PACID
  PACID=0.0
ENDIF
DO 105 JK=1,12
105 RLFL(IRLNO+1,JK)=0.0
RETURN
END

C.
C
SUBROUTINE RAT(RAT1,RAT2,I)
C CALCULATION OF PERCENTAGE OF UNITS COVERED DURING FLOODING
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
IF (IROR.EQ.1) GO TO 100
RAT1=(ALEV-ALED)/(ELPC-ELPB)
RAT2=(ALEV-ELPB)/(ELPC-ELPB)
RETURN
100 IF (ALEV.GT.UNEL(I+1)) GO TO 200
RAT1=0.0
RAT2=1.0
RETURN
200 IF (ALEV.LT.UNEL(I)) GO TO 300
RAT1=1.0
RAT2=0.0
RETURN
300 WIF=UNEL(I)-UNEL(I+1)
TIF=ALEV-UNEL(I+1)
RAT1=TIF/WIF
RAT2=1.0-RAT1
IF (ALEV.GT.ELPW-1.0) THEN RAT1=0.0
RETURN

```


END

C
C

SUBROUTINE PHS

C CALCULATION OF pH BASED ON ACIDITY AND ALKALINITY LEVELS

```
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
XACID=CACID-CALK
IF (XACID.LT.0.0) XACID=0.0
PHT=EXP(-0.0036*XACID)*7.57
RETURN
END
```

C
C

SUBROUTINE METAL

CALCULATION OF METAL LEVELS BASED ON pH

```
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
IF (PHT.LT.6.0) THEN
  CU=0.2
  ADIF=1.1-0.2
  BDIF=6.0-3.0
  CU=ADIF*(6.0-PHT)/BDIF+CU
ELSE
  CU=(-3.0)
  ADIF=0.20-(-3.00)
  BDIF=8.0-6.0
  CU=ADIF*(8.0-PHT)/BDIF+CU
ENDIF
CU=10.**(CU)
IF (PHT.LT.6.8) THEN
  FE=0.0
  ADIF=1.45-0.0
  BDIF=6.8-3.0
  FE=ADIF*(6.8-PHT)/BDIF+FE
ELSE
  FE=(-2.0)
  ADIF=0.0-(-2.0)
  BDIF=8.0-6.8
  FE=ADIF*(8.0-PHT)/BDIF+FE
ENDIF
FE=10.**(FE)
IF (PHT.LT.7.0) THEN
  ZN=0.10
  ADIF=1.10-0.10
  BDIF=7.0-3.0
  ZN=ADIF*(7.0-PHT)/BDIF+ZN
ELSE
  ZN=(-2.0)
  ADIF=0.10-(-2.00)
  BDIF=8.0-7.0
  ZN=ADIF*(8.0-PHT)/BDIF+ZN
ENDIF
ZN=10.**(ZN)
RETURN
END
```

C
C

```

SUBROUTINE INPT
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
CHARACTER*64 TITLE
READ (5,87) TITLE
87 FORMAT (A)
WRITE (6,88) TITLE
WRITE (*,88) TITLE
88 FORMAT (// ' ',A)
READ (5,1) ITOT
READ(5,1) ITIM
1 FORMAT (I5)
READ (5,1) ICOM
READ (5,1) IFLD
READ (5,1) IRLNO
READ (5,1) IROR
WRITE (6,83) ITOT
83 FORMAT (' PIT WALLS HAVE BEEN EXPOSED ',I5,'MONTHS PRIOR/' TO
'THE START OF THIS SIMULATION')
WRITE (6,50) ITIM
50 FORMAT (' TOTAL TIME OF SIMULATION = ',I5,'MONTHS')
IF (ICOM-1) 51,51,53
51 WRITE (6,54)
54 FORMAT (' ONLY ACTIVE OPERATION WILL BE SIMULATED')
GO TO 52
53 WRITE (6,55)
55 FORMAT (' OPERATION, FLOODING, AND DECOMMISSIONING WILL BE SIMULA
*TED')
52 IF (ICOM.EQ.2) WRITE (6,56) IFLD
56 FORMAT (' FLOODING BEGINS AT ELAPSED MONTH #',I5)
WRITE (6,57) IRLNO
57 FORMAT (// ' THERE ARE ',I5,'ROCK UNITS NOT INCLUDING PIT BOTTOM')
IF (IROR.EQ.1) THEN
WRITE (6,58)
58 FORMAT (// ' ROCK UNITS OCCUR AS HORIZONTAL BANDS AROUND THE'
* ' PERIMETER OF THE PIT'//)
ELSE
WRITE (6,59)
59 FORMAT (// ' ROCK UNITS OCCUR AS VERTICAL REGIONS EXTENDING'
* ' FROM PIT CREST TO PIT BOTTOM'//)
ENDIF
DO 100 I=1,IRLNO+1
READ (5,3) RLAR(I),RLHA(I),RLGL(I)
100 WRITE (6,49) I,RLAR(I),RLHA(I),RLGL(I)
49 FORMAT (' FOR ROCK UNIT ',I3,' TOTAL EXPOSED SURFACE AREA =',
*F14.3,'M^2/' OF WHICH ',F14.3,'M^2 ARE EXPOSED AS FLAT BENCHES
*') AND THE REMAINDER HAS A SLOPE OF ',F8.2,
*DEGREES FROM HORIZONTAL')
3 FORMAT (2F14.3,F8.2)
READ (5,4) (PREC(I),I=1,12)
4 FORMAT (6F8.2)
READ (5,4) (PRPB(I),I=1,12)
READ (5,4) (PRHA(I),I=1,12)
READ (5,4) (PRGL(I),I=1,12)
WRITE (6,60) (PREC(I),I=1,12)
60 FORMAT (// ' AVERAGE MONTHLY PRECIPITATION IN MILLIMETERS OVER A'
* ONE-YEAR PERIOD IS:'6F8.2/6F8.2)
WRITE (6,61) (PRPB(I),I=1,12)
61 FORMAT (// ' AVERAGE MONTHLY RAINFALL ON PIT BOTTOM (IN MM):'
*6F8.2/6F8.2)
WRITE (6,62) (PRHA(I),I=1,12)
62 FORMAT (// ' AVERAGE MONTHLY RAINFALL ON FLAT BENCHES (MM):'
*6F8.2/6F8.2)
WRITE (6,63) (PRGL(I),I=1,12)
63 FORMAT (// ' AVERAGE MONTHLY RAINFALL ON SLOPING WALLS (MM):'

```

```

*6F8.2/6F8.2)
READ(5,5) (GWST(I),I=1,12)
5 FORMAT (6F12.2)
WRITE (6,64) (GWST(I),I=1,12)
64 FORMAT (// ' AVERAGE MONTHLY GROUNDWATER INFLOW FROM SATURATED ZONE
* M^3/MONTH):'6F12.2/6F12.2//)
DO 101 I=1,IRLNO
READ (5,5) (GWUS(I,J),J=1,12)
101 WRITE (6,65) I,(GWUS(I,J),J=1,12)
65 FORMAT (' MONTHLY UNSATURATED FRACTURE FLOW (M^3/MONTH) FOR UNIT'
*,I3,': '6F12.2/6F12.2)
WRITE (6,67)
67 FORMAT (//)
DO 102 I=1,IRLNO
READ (5,6) (RATE(I,J),J=1,12)
6 FORMAT (6F8.2)
102 WRITE (6,66) I,(RATE(I,J),J=1,12)
66 FORMAT (' MONTHLY RATE OF ACID GENERATION (MG SO4/MONTH/M^2) FOR U
*NIT',I3/6F8.2/6F8.2)
WRITE (6,68)
68 FORMAT (' ** THESE RATES ARE ASSUMED TO DECREASE 5%/YEAR EACH YEAR
**/ ' RESULTING IN CUMULATIVE 40.2% AND 92.3% DECREASES AFTER'
*/ ' 10 AND 50 YEARS, RESPECTIVELY **//)
DO 103 I=1,IRLNO
READ (5,7) TOTS(I)
7 FORMAT (F8.2)
103 WRITE (6,80) I,TOTS(I)
80 FORMAT (' FOR UNIT ',I3,' TOTAL EXPOSED SULFUR IS ',F8.2,' GRAMS S
* / M^2')
WRITE (6,70)
70 FORMAT (// ' FOR EACH SQUARE METER OF PIT WALL,')
DO 104 I=1,IRLNO
READ (5,8) OFS(I)
8 FORMAT (F7.2)
104 WRITE (6,69) I,OFS(I)
69 FORMAT (' UNIT ',I3,' HAS ',F7.2,' M^2 OF FRACTURE SURFACE')
WRITE (6,72)
72 FORMAT (// ' FRACTURE FLUSHING AS A PERCENTAGE OF SURFACE:')
DO 105 I=1,IRLNO
READ (5,9) (OFT(I,J),J=1,3)
9 FORMAT (3F7.2)
105 WRITE (6,71) I,(OFT(I,J),J=1,3)
71 FORMAT (' UNIT ',I3,': MONTHLY='F6.2,'% YEARLY='F6.2,'% NONE
*='F7.2,'%')
READ (5,1) IMFL
READ (5,10) ALKS,ALKU,BSOT
10 FORMAT (3F8.2)
WRITE (6,81) IMFL,ALKS,BSOT,ALKU
81 FORMAT (// ' YEARLY FRACTURE FLUSHING OCCURS IN MONTH ',I3//
** ALKALINITY OF SATURATED-ZONE INFLOW = ',F8.2,' MG CACO3/L/'
** SULFATE OF SATURATED-ZONE INFLOW = ',F8.2,' MG SO4/L/'
** ALKALINITY OF UNSATURATED-ZONE FLOW = ',F8.2,' MG CACO3/L//)
DO 106 I=1,IRLNO
READ (5,11) TOK(I,I)
11 FORMAT (F12.3)
106 WRITE (6,73) I,TOK(I,I)
73 FORMAT (' UNIT ',I3,' HAS ',F12.3,' GR CACO3 EXPOSED ON 1 M^2 OF SU
*RFACE')
IF (ICOM.EQ.1) GO TO 85
READ (5,12) GWEQ,ELPW,ELPB,ELPC
12 FORMAT (4F14.4)
WRITE (6,74) GWEQ,ELPW,ELPB,ELPC
74 FORMAT (/// ' ** FOR DECOMMISSIONING **// ' STEADY-STATE GROUNDWATE
*R FLOW THROUGH FLOODED PIT='F14.4' WHEN THE WATER LEVEL REACHE
*S THE STEADY-STATE ELEVATION OF ',F9.2,' M.A.S.L.'// ' FINAL PIT BO
*TTOM ELEVATION= ',F9.2,' M.A.S.L.'// 'PIT CREST ELEVATION = ',F9.2,
** M.A.S.L.'//)
K=0
WRITE (6,75)
75 FORMAT (// ' STORAGE CAPACITY OF THE PIT IN M^3 BEGINNING AT PIT BOT
*TOM:')

```

```

108 K=K+1
  READ (5,13) ELEV(K),PITC(K)
13 FORMAT (F8.2,F16.3)
  IF (ELEV(K).EQ.(-1.0)) GO TO 107
  WRITE (6,76) ELEV(K),PITC(K)
76 FORMAT (' AT ELEVATION ',F8.2,' CAPACITY IS ',F16.3)
  GO TO 108
107 IF (IROR.NE.1) GO TO 85
  WRITE (6,77)
77 FORMAT (// ' ELEVATIONS OF TOPS OF HORIZONTAL ROCK BANDS AND PIT BO
  *TTOM:')
  DO 109 I=1,IRLNO+1
  READ (5,14) UNEL(I)
14 FORMAT (F8.2)
109 WRITE (6,78) I,UNEL(I)
78 FORMAT (' TOP OF UNIT ',I3,' IS AT ',F9.2,M.A.S.L.)
  WRITE (6,79)
79 FORMAT (' ** LAST UNIT IS PIT BOTTOM **')
85 WRITE (6,86)
86 FORMAT (/// ' *****SIMULATION BEGINS *****')
  RETURN
  END

```

C
C

```

SUBROUTINE OUT1
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
WRITE (6,1) KTIM,IYR,IMON
1 FORMAT (/// ' ELAPSED TIME = ',I5,' MONTHS   OR ',I4,' YEARS AND ',
*I3,' MONTHS')
TOT=TOTF/1000.
WRITE (6,2) TOT
2 FORMAT (' TOTAL FLOW INTO THE MINE = ',F12.3,M^3/MONTH')
WRITE (6,3) PHT,CSO4,XACID,CU,FE,ZN
3 FORMAT (' pH= ',F6.2,' ln mg/L: SULFATE= ',F9.3,' EXCESS ACIDI
*TY= ',F9.3,' Cu= ',F10.5,' Fe= ',F10.5,' Zn= ',F10.5)
WRITE (*,4) KTIM
4 FORMAT (' ELAPSED TIME = ',I5,' MONTHS')
RETURN
END

```

C
C

```

SUBROUTINE OUT2
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
IELT=KTIM-IFLD
WRITE (6,1) KTIM,IELT
1 FORMAT (/// ' TOTAL ELAPSED TIME = ',I5,' MONTHS/' TIME SINCE INI
*TATION OF FLOODING = ',I5,' MONTHS')
WRITE (6,2) ALEV,PVOL
2 FORMAT (' ELEVATION OF WATER LEVEL IN THE MINE= ',F8.2/
*' REPRESENTING A WATER VOLUME OF ',F12.2,M^3')
WRITE (6,3) PHT,CSO4,XACID,CU,FE,ZN
3 FORMAT (' pH= ',F6.2,' ln mg/L: SULFATE= ',F9.3,' EXCESS ACIDI
*TY= ',F9.3,' Cu= ',F10.5,' Fe= ',F10.5,' Zn= ',F10.5)
WRITE (*,4) KTIM
4 FORMAT (' ELAPSED TIME = ',I5,' MONTHS')
RETURN
END

```

C
C

```

SUBROUTINE OUT3
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
TOT=TOTF/1000.
WRITE (7,1) KTIM,ELPB,TOT,CSO4,PHT,CU,FE,ZN
1 FORMAT (I4,F8.2,F14.3,2F8.2,3F10.5)
RETURN
END

```

C
C

```

SUBROUTINE OUT4
COMMON /BLOCK1/RLAR(20),RLHA(20),RLGL(20),TOTS(20),OFS(20),
*UNEL(20),RLMM(20),RLNN(20),PITC(40),ELEV(40),PREC(13),PRHA(13),
*PRGL(13),PRPB(13),GWST(13),YRAT(13),GWUS(20,13),RATE(20,13),
*RLFL(20,13),GWUU(20,13),OFT(20,4),TOK(4,20),TSO(6,20),TAL(4,20),
*IRLNO
COMMON /BLOCK2/TOTF,CSO4,CALK,CACID,PHT,CU,FE,ZN,PACID,PALK,ALEV,
*PVOL,ELDIF,FLDIF,GWEQ,ELPW,ELPB,ELPC,ALKS,ALKU,XACID,AFLN,ALED,
*BSOT,PSO4,IMFL,IROR,IFLD,ICOM,ITIM,KTIM,IYR,IMON,ITOT
WRITE (7,1) KTIM,ALEV,PVOL,CSO4,PHT,CU,FE,ZN
1 FORMAT (I4,F8.2,F14.2,2F8.2,3F10.5)
RETURN
END

```

D2. Sample Input File

This file was created using the PREMINE preprocessor.

EQUITY MAIN ZONE PIT

```

40
100
2
31
3
2
315000.000 110250.00070.00
234000.000 81900.00070.00
214000.000 74900.00070.00
37000.000 37000.000 0.00
8.30 1.70 6.50 4.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 9.30
8.30 1.70 6.50 4.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 9.30
0.00 0.00 18.10 32.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 0.00
0.00 0.00 18.10 32.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 0.00
25000.00 25000.00 30000.00 30000.00 25000.00 25000.00
25000.00 25000.00 25000.00 25000.00 25000.00 25000.00
41.30 41.30 41.30 8260.00 1239.00 1239.00
1239.00 1239.00 1239.00 1239.00 1239.00 41.30
30.70 30.70 30.70 6140.00 921.00 921.00
921.00 921.00 921.00 921.00 921.00 30.70
28.00 28.00 28.00 5600.00 840.00 840.00
840.00 840.00 840.00 840.00 840.00 28.00
33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50
33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50
33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50
48.00
64.00
144.00
20.00
40.00
40.00
28.00 2.00 70.00
28.00 2.00 70.00
28.00 2.00 70.00
4
150.00 150.00 400.00
225.000
100.000
25.000
10000.0000 1282.0000 1120.0000 1320.0000
1120.00 0.000
1140.00 896000.000
1160.00 2000000.000
1180.00 3380000.000
1200.00 5060000.000
1220.00 7070000.000
1240.00 9500000.000
1260.00 12200000.000
1280.00 15300000.000
1282.00 15600000.000
-1.00

```

D3. Sample Output

This output file was created by MINEWALL using the preceding input data file. This sample output is truncated due to its length.

EQUITY MAIN ZONE PIT

PIT WALLS HAVE BEEN EXPOSED 40 MONTHS PRIOR
TO THE START OF THIS SIMULATION

TOTAL TIME OF SIMULATION = 100 MONTHS

OPERATION, FLOODING, AND DECOMMISSIONING WILL BE SIMULATED

FLOODING BEGINS AT ELAPSED MONTH # 31

THERE ARE 3 ROCK UNITS NOT INCLUDING PIT BOTTOM

ROCK UNITS OCCUR AS VERTICAL REGIONS EXTENDING
FROM PIT CREST TO PIT BOTTOM

FOR ROCK UNIT 1

TOTAL EXPOSED SURFACE AREA = 315000.000M²
OF WHICH 110250.000M² ARE EXPOSED AS FLAT BENCHES
AND THE REMAINDER HAS A SLOPE OF 70.00DEGREES FROM HORIZONTAL

FOR ROCK UNIT 2

TOTAL EXPOSED SURFACE AREA = 234000.000M²
OF WHICH 81900.000M² ARE EXPOSED AS FLAT BENCHES
AND THE REMAINDER HAS A SLOPE OF 70.00DEGREES FROM HORIZONTAL

FOR ROCK UNIT 3

TOTAL EXPOSED SURFACE AREA = 214000.000M²
OF WHICH 74900.000M² ARE EXPOSED AS FLAT BENCHES
AND THE REMAINDER HAS A SLOPE OF 70.00DEGREES FROM HORIZONTAL

FOR ROCK UNIT 4

TOTAL EXPOSED SURFACE AREA = 37000.000M²
OF WHICH 37000.000M² ARE EXPOSED AS FLAT BENCHES
AND THE REMAINDER HAS A SLOPE OF .00DEGREES FROM HORIZONTAL

AVERAGE MONTHLY PRECIPITATION IN MILLIMETERS OVER A
ONE-YEAR PERIOD IS:

8.30 1.70 6.50 4.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 9.30

AVERAGE MONTHLY RAINFALL ON PIT BOTTOM (IN MM):

8.30 1.70 6.50 4.30 40.00 56.10

71.10 108.40 32.00 70.10 4.80 9.30

AVERAGE MONTHLY RAINFALL ON FLAT BENCHES (MM):

.00 .00 18.10 32.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 .00

AVERAGE MONTHLY RAINFALL ON SLOPING WALLS (MM):

.00 .00 18.10 32.30 40.00 56.10
71.10 108.40 32.00 70.10 4.80 .00

AVERAGE MONTHLY GROUNDWATER INFLOW FROM SATURATED ZONE M³/MONTH):
25000.00 25000.00 30000.00 30000.00 25000.00 25000.00 25000.00 25000.00 25000.00 25000.00
25000.00 25000.00

MONTHLY UNSATURATED FRACTURE FLOW (M³/MONTH) FOR UNIT 1:

41.30 41.30 41.30 8260.00 1239.00 1239.00 1239.00 1239.00 1239.00 1239.00 1239.00
41.30

MONTHLY UNSATURATED FRACTURE FLOW (M³/MONTH) FOR UNIT 2:

30.70 30.70 30.70 6140.00 921.00 921.00
921.00 921.00 921.00 921.00 921.00 30.70

MONTHLY UNSATURATED FRACTURE FLOW (M³/MONTH) FOR UNIT 3:

28.00 28.00 28.00 5600.00 840.00 840.00
840.00 840.00 840.00 840.00 840.00 28.00

MONTHLY RATE OF ACID GENERATION (MG SO₄/MONTH/M²) FOR UNIT 1

33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50

MONTHLY RATE OF ACID GENERATION (MG SO₄/MONTH/M²) FOR UNIT 2

33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50

MONTHLY RATE OF ACID GENERATION (MG SO₄/MONTH/M²) FOR UNIT 3

33.50 33.50 33.50 334.60 334.60 334.60
334.60 334.60 334.60 334.60 334.60 33.50

** THESE RATES ARE ASSUMED TO DECREASE 5%/YEAR EACH YEAR
RESULTING IN CUMULATIVE 40.2% AND 92.3% DECREASES AFTER
10 AND 50 YEARS, RESPECTIVELY **

FOR UNIT 1 TOTAL EXPOSED SULFUR IS 48.00 GRAMS S / M²

FOR UNIT 2 TOTAL EXPOSED SULFUR IS 64.00 GRAMS S / M²

FOR UNIT 3 TOTAL EXPOSED SULFUR IS 144.00 GRAMS S / M²

FOR EACH SQUARE METER OF PIT WALL,

UNIT 1 HAS 20.00 M² OF FRACTURE SURFACE

UNIT 2 HAS 40.00 M² OF FRACTURE SURFACE

UNIT 3 HAS 40.00 M² OF FRACTURE SURFACE

FRACTURE FLUSHING AS A PERCENTAGE OF SURFACE:

UNIT 1: MONTHLY= 28.00% YEARLY= 2.00% NONE = 70.00%
 UNIT 2: MONTHLY= 28.00% YEARLY= 2.00% NONE = 70.00%
 UNIT 3: MONTHLY= 28.00% YEARLY= 2.00% NONE = 70.00%

YEARLY FRACTURE FLUSHING OCCURS IN MONTH 4

ALKALINITY OF SATURATED-ZONE INFLOW = 150.00MG CACO3/L
 SULFATE OF SATURATED-ZONE INFLOW = 400.00MG SO4/L
 ALKALINITY OF UNSATURATED-ZONE FLOW = 150.00MG CACO3/L

UNIT 1 HAS 225.000GR CACO3 EXPOSED ON 1 M² OF SURFACE
 UNIT 2 HAS 100.000GR CACO3 EXPOSED ON 1 M² OF SURFACE
 UNIT 3 HAS 25.000GR CACO3 EXPOSED ON 1 M² OF SURFACE

** FOR DECOMMISSIONING **

STEADY-STATE GROUNDWATER FLOW THROUGH FLOODED PIT= 10000.0000
 WHEN THE WATER LEVEL REACHES THE STEADY-STATE ELEVATION OF 1282.00M.A.S.L.

FINAL PIT BOTTOM ELEVATION= 1120.00M.A.S.L.
 PIT CREST ELEVATION = 1320.00M.A.S.L.

STORAGE CAPACITY OF THE PIT IN M³ BEGINNING AT PIT BOTTOM:

AT ELEVATION	1120.00	CAPACITY IS	.000
AT ELEVATION	1140.00	CAPACITY IS	896000.000
AT ELEVATION	1160.00	CAPACITY IS	2000000.000
AT ELEVATION	1180.00	CAPACITY IS	3380000.000
AT ELEVATION	1200.00	CAPACITY IS	5060000.000
AT ELEVATION	1220.00	CAPACITY IS	7070000.000
AT ELEVATION	1240.00	CAPACITY IS	9500000.000
AT ELEVATION	1260.00	CAPACITY IS	12200000.000
AT ELEVATION	1280.00	CAPACITY IS	15300000.000
AT ELEVATION	1282.00	CAPACITY IS	15600000.000

*****SIMULATION BEGINS*****

ELAPSED TIME = 1 MONTHS OR 0 YEARS AND 1 MONTHS

TOTAL FLOW INTO THE MINE = 25407.100M³/MONTH

pH= 7.57

In mg/L: SULFATE= 402.533 EXCESS ACIDITY= .000

Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 2 MONTHS OR 0 YEARS AND 2 MONTHS
 TOTAL FLOW INTO THE MINE = 25162.900M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 406.439 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 3 MONTHS OR 0 YEARS AND 3 MONTHS
 TOTAL FLOW INTO THE MINE = 40859.220M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 299.877 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 4 MONTHS OR 0 YEARS AND 4 MONTHS
 TOTAL FLOW INTO THE MINE = 68930.070M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 213.770 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 5 MONTHS OR 0 YEARS AND 5 MONTHS
 TOTAL FLOW INTO THE MINE = 52725.790M³/MONTH
 pH= 7.12
 In mg/L: SULFATE= 237.539 EXCESS ACIDITY= 16.958
 Cu= .02543 Fe= .29099 Zn= .69900

ELAPSED TIME = 6 MONTHS OR 0 YEARS AND 6 MONTHS
 TOTAL FLOW INTO THE MINE = 62677.910M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 199.822 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 7 MONTHS OR 0 YEARS AND 7 MONTHS
 TOTAL FLOW INTO THE MINE = 71950.090M³/MONTH
 pH= 7.18
 In mg/L: SULFATE= 174.071 EXCESS ACIDITY= 14.722
 Cu= .02057 Fe= .23330 Zn= .52913

ELAPSED TIME = 8 MONTHS OR 0 YEARS AND 8 MONTHS
 TOTAL FLOW INTO THE MINE = 95006.880M³/MONTH
 pH= 7.27
 In mg/L: SULFATE= 131.826 EXCESS ACIDITY= 11.149
 Cu= .01460 Fe= .16331 Zn= .33760

ELAPSED TIME = 9 MONTHS OR 0 YEARS AND 9 MONTHS
 TOTAL FLOW INTO THE MINE = 47780.630M³/MONTH
 pH= 6.99
 In mg/L: SULFATE= 262.123 EXCESS ACIDITY= 22.168
 Cu= .04140 Fe= .48353 Zn= 1.26667

ELAPSED TIME = 10 MONTHS OR 0 YEARS AND 10 MONTHS
 TOTAL FLOW INTO THE MINE = $71331.950\text{M}^3/\text{MONTH}$
 pH= 7.18
 In mg/L: SULFATE= 175.579 EXCESS ACIDITY= 14.849
 Cu= .02082 Fe= .23627 Zn= .53763

ELAPSED TIME = 11 MONTHS OR 0 YEARS AND 11 MONTHS
 TOTAL FLOW INTO THE MINE = $30967.100\text{M}^3/\text{MONTH}$
 pH= 6.69
 In mg/L: SULFATE= 404.443 EXCESS ACIDITY= 34.205
 Cu= .12338 Fe= 1.09861 Zn= 1.50231

ELAPSED TIME = 12 MONTHS OR 0 YEARS AND 12 MONTHS
 TOTAL FLOW INTO THE MINE = $25444.100\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 401.947 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 13 MONTHS OR 1 YEARS AND 1 MONTHS
 TOTAL FLOW INTO THE MINE = $25407.100\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 402.085 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 14 MONTHS OR 1 YEARS AND 2 MONTHS
 TOTAL FLOW INTO THE MINE = $25162.900\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 405.988 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 15 MONTHS OR 1 YEARS AND 3 MONTHS
 TOTAL FLOW INTO THE MINE = $40859.220\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 299.568 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 16 MONTHS OR 1 YEARS AND 4 MONTHS
 TOTAL FLOW INTO THE MINE = $68930.070\text{M}^3/\text{MONTH}$
 pH= 7.45
 In mg/L: SULFATE= 228.481 EXCESS ACIDITY= 4.510
 Cu= .00764 Fe= .08315 Zn= .14422

ELAPSED TIME = 17 MONTHS OR 1 YEARS AND 5 MONTHS
 TOTAL FLOW INTO THE MINE = $52725.790\text{M}^3/\text{MONTH}$
 pH= 7.17
 In mg/L: SULFATE= 235.145 EXCESS ACIDITY= 15.102
 Cu= .02133 Fe= .24226 Zn= .55487

ELAPSED TIME = 18 MONTHS OR 1 YEARS AND 6 MONTHS
 TOTAL FLOW INTO THE MINE = $62677.910\text{M}^3/\text{MONTH}$
 pH= 7.23
 In mg/L: SULFATE= 197.808 EXCESS ACIDITY= 12.704
 Cu= .01696 Fe= .19085 Zn= .41083

ELAPSED TIME = 19 MONTHS OR 1 YEARS AND 7 MONTHS
 TOTAL FLOW INTO THE MINE = $71950.090\text{M}^3/\text{MONTH}$
 pH= 7.27
 In mg/L: SULFATE= 172.317 EXCESS ACIDITY= 11.067
 Cu= .01449 Fe= .16197 Zn= .33411

ELAPSED TIME = 20 MONTHS OR 1 YEARS AND 8 MONTHS
 TOTAL FLOW INTO THE MINE = $95006.880\text{M}^3/\text{MONTH}$
 pH= 7.35
 In mg/L: SULFATE= 130.498 EXCESS ACIDITY= 8.381
 Cu= .01117 Fe= .12349 Zn= .23740

ELAPSED TIME = 21 MONTHS OR 1 YEARS AND 9 MONTHS
 TOTAL FLOW INTO THE MINE = $47780.630\text{M}^3/\text{MONTH}$
 pH= 7.13
 In mg/L: SULFATE= 259.482 EXCESS ACIDITY= 16.665
 Cu= .02473 Fe= .28270 Zn= .67401

ELAPSED TIME = 22 MONTHS OR 1 YEARS AND 10 MONTHS
 TOTAL FLOW INTO THE MINE = $71331.950\text{M}^3/\text{MONTH}$
 pH= 7.27
 In mg/L: SULFATE= 173.810 EXCESS ACIDITY= 11.163
 Cu= .01462 Fe= .16354 Zn= .33819

ELAPSED TIME = 23 MONTHS OR 1 YEARS AND 11 MONTHS
 TOTAL FLOW INTO THE MINE = $30967.100\text{M}^3/\text{MONTH}$
 pH= 6.90
 In mg/L: SULFATE= 400.367 EXCESS ACIDITY= 25.713
 Cu= .05739 Fe= .67940 Zn= 1.33296

ELAPSED TIME = 24 MONTHS OR 1 YEARS AND 12 MONTHS
 TOTAL FLOW INTO THE MINE = $25444.100\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 401.501 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 25 MONTHS OR 2 YEARS AND 1 MONTHS
 TOTAL FLOW INTO THE MINE = $25407.100\text{M}^3/\text{MONTH}$
 pH= 7.57
 In mg/L: SULFATE= 401.661 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 26 MONTHS OR 2 YEARS AND 2 MONTHS
 TOTAL FLOW INTO THE MINE = 25162.900M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 405.559 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 27 MONTHS OR 2 YEARS AND 3 MONTHS
 TOTAL FLOW INTO THE MINE = 40859.220M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 299.274 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 28 MONTHS OR 2 YEARS AND 4 MONTHS
 TOTAL FLOW INTO THE MINE = 68930.070M³/MONTH
 pH= 7.57
 In mg/L: SULFATE= 225.761 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

ELAPSED TIME = 29 MONTHS OR 2 YEARS AND 5 MONTHS
 TOTAL FLOW INTO THE MINE = 52725.790M³/MONTH
 pH= 7.29
 In mg/L: SULFATE= 232.871 EXCESS ACIDITY= 10.364
 Cu= .01354 Fe= .15091 Zn= .30562

ELAPSED TIME = 30 MONTHS OR 2 YEARS AND 6 MONTHS
 TOTAL FLOW INTO THE MINE = 62677.910M³/MONTH
 pH= 7.34
 In mg/L: SULFATE= 195.895 EXCESS ACIDITY= 8.718
 Cu= .01154 Fe= .12779 Zn= .24785

**** DECOMMISSIONING BEGINS ****

TOTAL ELAPSED TIME = 31 MONTHS
 TIME SINCE INITIATION OF FLOODING = 0 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1120.50
 REPRESENTING A WATER VOLUME OF 22236.97M³
 pH= 5.89
 In mg/L: SULFATE= 515.283 EXCESS ACIDITY= 69.736
 Cu= 1.71079 Fe= 2.22580 Zn= 2.38596

TOTAL ELAPSED TIME = 32 MONTHS
 TIME SINCE INITIATION OF FLOODING = 1 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1120.99
 REPRESENTING A WATER VOLUME OF 44473.68M³
 pH= 7.57
 In mg/L: SULFATE= 464.184 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 33 MONTHS
 TIME SINCE INITIATION OF FLOODING = 2 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1121.49
 REPRESENTING A WATER VOLUME OF 66709.60M³
 pH= 7.57
 In mg/L: SULFATE= 447.237 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 34 MONTHS
 TIME SINCE INITIATION OF FLOODING = 3 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1121.99
 REPRESENTING A WATER VOLUME OF 88944.20M³
 pH= 7.57
 In mg/L: SULFATE= 438.828 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 35 MONTHS
 TIME SINCE INITIATION OF FLOODING = 4 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1122.48
 REPRESENTING A WATER VOLUME OF 111176.90M³
 pH= 7.57
 In mg/L: SULFATE= 433.835 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 36 MONTHS
 TIME SINCE INITIATION OF FLOODING = 5 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1122.98
 REPRESENTING A WATER VOLUME OF 133407.30M³
 pH= 7.57
 In mg/L: SULFATE= 430.356 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 37 MONTHS
 TIME SINCE INITIATION OF FLOODING = 6 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1123.47
 REPRESENTING A WATER VOLUME OF 155634.80M³
 pH= 7.57
 In mg/L: SULFATE= 427.874 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998

TOTAL ELAPSED TIME = 38 MONTHS
 TIME SINCE INITIATION OF FLOODING = 7 MONTHS
 ELEVATION OF WATER LEVEL IN THE MINE= 1123.97
 REPRESENTING A WATER VOLUME OF 177858.80M³
 pH= 7.57
 In mg/L: SULFATE= 426.015 EXCESS ACIDITY= .000
 Cu= .00488 Fe= .05208 Zn= .07998