HYDROGEOLOGICAL SITE CHARACTERIZATION
IN AN ACID ROCK DRAINAGE MANAGEMENT PROGRAM

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ABSTRACT

Surface and subsurface hydrological processes play important roles in the flushing and transport of acid rock drainage. A thorough understanding of the hydrogeologic regime at proposed mine sites and sites generating acid rock drainage is therefore necessary prior to the initiation of an ARD management program. The hydrogeological site characterization should establish the regional hydrogeological setting, local baseline groundwater quality, the local hydrogeologic regime geometry, hydrogeologic parameters of hydrostratigraphic units and site specific flow conditions. The site characterization involves a regional study, the site investigation and site groundwater flow assessment.

Available hydrogeological data from the abandoned Mount Washington Mine located on Vancouver Island will be reviewed and the site will be used as an example to demonstrate the importance of groundwater in ARD flushing and transport. The mine was in operation through the mid-1960's. Acidic rock drainage and associated elevated copper concentrations generated in the North Pit of the site have been implicated in fishery losses in the Tsolum River. Strong hydrogeological controls on ARD flushing and transport have been identified but the hydrogeologic regime of the site is still not well understood.

INTRODUCTION

Acid rock drainage, ARD, is the most important environmental concern in mining in B.C. today. Steps are being taken at developing mine sites in order to prevent ARD generation through prediction and design in order to avoid the costs of long term treatment. At operating mine sites, work is being done to limit ARD production and control its impact.

Groundwater movement through and beneath ARD generating material is a primary pathway for contaminant migration. Acidic drainage may be transported from the site of production through the flushing of groundwater flow. The contaminated groundwater may then discharge down gradient as seeps or springs, for example, at the toe of a waste rock dump or, alternatively, may discharge as base flow into adjacent streams or lakes, in both cases potentially impacting aquatic populations. A site specific understanding of the role of hydrogeologic regime is, therefore, a prerequisite to the understanding and prediction of the migration of ARD. Furthermore, this understanding is a requirement in the development
of mine designs that minimize the role of groundwater in ARD production and transport and for the implementation of control measures.

The general approaches to ARD control include: (1) the control of oxidation and the ARD generation process, (2) the control of contaminant migration, and (3) the collection and treatment of contaminated drainage (Steffen, Robertson and Kirsten, 1992). Oxidation processes may be limited through the flooding of underground workings and open pits. Contaminant migration control involves reducing ARD flushing through limiting the infiltration of water through the use of covers on tailings and waste rock piles and by limiting the flow of ground or surface water towards tailings and waste rock piles by interception and diversion strategies. The collection and treatment of contaminated drainage in the subsurface is facilitated by intercepting ARD in the subsurface through ditches, trenches or by subsurface pumping. A sound knowledge of the groundwater regime is necessary to implement any of these types of control measures.

The hydrogeological site characterization is, therefore, an important part of any ARD management program. This paper summarizes the steps involved in a hydrogeological site characterization for active and new mine sites, with specific focus on the role of groundwater in ARD flushing and transport.

HYDROGEOLOGY - GENERAL PRINCIPLES AND THE RELATIONSHIP TO ARD

Hydrogeology may be considered as the study of the movement of subterranean water and the interaction of this water with the porous media through which it flows. Hydrology is the study of water and its processes both above ground and in the subsurface. Hydrogeology may be considered a synonym for subsurface hydrology, geohydrology and groundwater hydrology.

The Hydrologic Cycle
Water is introduced to the subsurface through the infiltration of precipitation in the form of rain or snow melt. Precipitation falls and evaporates, infiltrates or flows on the ground surface as overland flow. Water flows through the unsaturated zone, the area where water and air fill pore spaces, and recharges the saturated zone, the area where the pore spaces are filled with water. Figure 1 shows components of the hydrologic cycle.

Components of the Groundwater Regime
Groundwater recharge occurs at areas where infiltrating precipitation or surface water adds to the groundwater. Recharge areas are typically located in topographic highs. Groundwater discharge occurs at areas where groundwater leaves the subsurface. Discharge may occur in the form of springs, seeps, transpiration or as base flow to streams. The water table occurs below a deep unsaturated zone in
topographic highs but close to the surface in discharge zones. Groundwater divides are topographic highs where groundwater flows in opposite directions. Groundwater divides are analogous to, and often coincide with, basin divides where surface run-off is constrained to one drainage basin. Figure 2 shows components of a groundwater regime within a basin. Included in this schematic are three waste rock piles.

Figure 1. Basin hydrologic cycle schematic

Figure 2. Basinal groundwater flow regime including the location of three waste piles

Topographically controlled regional flow systems may have well developed local flow systems which may result in local discharge zones located within recharge areas. An example of the importance of defining recharge and discharge areas is illustrated by considering three potential waste rock dump locations as shown in Figure 2.
The first waste rock pile is located in a recharge area. A water table is developed within the pile due to the infiltration of precipitation alone. The second waste rock pile is located in the center of a discharge area. The water table in this waste rock pile is a product of the infiltration of precipitation and the discharge of groundwater. The third waste rock pile is located between a recharge and discharge area. Once again, the water table developed is partially a function of groundwater flow (Morin et al., 1991).

Acid drainage control measures involving impermeable covers may be suitable in the first case. However, ARD transport would not be prevented by covering alone in cases two and three. In these cases, the reduction of flushing and transport would have to involve reducing the effect of groundwater.

Aquifer Types
Unconfined aquifers are those that exist close to the land surface in a material of high hydraulic conductivity that extends from the land surface to the base of the aquifer. (Fetter 1988). Confined aquifers are aquifers bounded by layers of rock or soil of relatively low hydraulic conductivity. The confined aquifer has a potentiometric surface that exceeds that which exists within the upper confining layer. Fracture zones of relatively higher hydraulic conductivity may behave as confined aquifers. The characteristics of confined aquifers, if present, must be determined to assess their influence on the local and regional flow regime and hence ARD transport.

Perched aquifers are saturated zones underlain by unsaturated zones. Perched aquifers may develop where infiltrating water intersects material of low hydraulic conductivity. The development of perched aquifers in a waste rock dump can result in seeps or groundwater discharge out of the waste rock dump above the surrounding ground surface.

Hydraulic Conductivity
Hydraulic conductivity is generally the most important soil or rock parameter when considering the volume or velocity of groundwater flow through a porous media. It is a function of the amount, tortuosity and size of interconnected pore spaces within the porous media. In competent rock, hydraulic conductivity will be more a function of the width and density of fractures. Groundwater flow velocities in fractured competent rock may also rely heavily on effective porosities. Low effective porosities result in high flow rates.

Acid rock drainage transport (flux and velocity) is a function of the area in which it is being produced and will rely heavily on hydraulic conductivities of soil and rock units present. Waste rock dumps, for example, often exhibit varying degrees of hydraulic conductivity with its distribution within the pile being partially dependent on the method of construction. Zones of lower or higher hydraulic conductivity may develop. Zones of relatively higher hydraulic conductivity result in channeling, where the bulk of
groundwater flow is focused through the permeable zone. In addition, perched water tables may develop above fine grained layers within waste rock piles as previously discussed.

THE HYDROGEOLOGIC SITE CHARACTERIZATION

Objectives
A site should be characterized with respect to hydrogeology to achieve the following objectives:

1. to establish the hydrogeological setting of the site,
2. to establish base line conditions with respect to water quality
3. to determine the geometry of the hydrogeologic regime across the site,
4. to determine the numerical value of hydrogeological parameters of the hydrostratigraphic units comprising the flow system across the site,
5. to determine site specific flow conditions, i.e. volumetric discharge, groundwater velocity

A hydrogeologic site characterization will allow the prediction of how hydrogeologic conditions will change as a result of the mining operation, the prediction of the role of groundwater in ARD migration, and the prediction of the response of the system to remedial and control measures.

Steps In Conducting A Hydrogeological Site Characterization
The hydrogeologic site characterization should include (1) a study of the regional drainage basin in which the site is located, in order to determine the overall hydrogeologic setting of the site, and (2) a study of the mine site. Once the components of the regional groundwater regime are determined, the site investigation is conducted. This involves the determination of the geometry and characteristics of the groundwater regime on site, and its interrelationship with regional hydrogeology and the determination of hydrogeological parameters of rock and soil units. Conceptual and numerical models can then be developed to simplify the field problem, organize the associated field data to facilitate system analysis, and to allow the prediction of changes to the groundwater flow regime following the application of remedial or control measures.

Regional (Drainage Basin) Study
The regional hydrogeological assessment involves a review of available information and may be completed over days or weeks, depending on the scope of the project, as a desk study. The study involves an assessment of the physiography, geomorphology and quaternary geology, climate, surface hydrology and bedrock geology of the catchment basin.
A list of pertinent study areas, the important characteristics of each area, and information sources for the regional study is summarized in Table 1.

Site Investigation
Following the review of the findings of the regional study, detailed local studies are carried out to determine the distribution of soil and rock hydrostratigraphic units on site to define the geometry of the local groundwater regime, to determine individual hydrogeologic parameters of the units and to determine groundwater geochemistry. The study areas, important characteristics of the areas, and information sources and site study types are summarized in Table 2.

In addition to the areas of study in the regional and site investigations, during the site investigation groundwater should be assessed to determine background water quality, the quality of water entering the site and the concentration and spatial distribution of ARD in the subsurface across ARD producing sites. Temporal variations in water quality are also important and water quality assessment may be completed over the period of a year.

Site Groundwater Flow Assessment and Modeling the Hydrogeologic Regime
Following the field programs, the groundwater flow across the site within individual aquifers must be assessed. This assessment generally involves the determination of groundwater gradients, flow directions, fluxes and velocities within the unconfined aquifer.

The assessment of site specific flow conditions may be completed through numerical modeling. The conceptual model is an initial step in the generation of a numerical model and is a pictorial representation of the groundwater flow system. The conceptual model simplifies the field problem and organizes the associated field data so that the system may be analyzed. Numerical modeling allows the prediction of changes to the groundwater flow regime following remedial or control measures and an assessment of the effectiveness of the selected technique.

Site Characterization Philosophy
Much information collected during the initial exploration stage of a mining project may be valuable in hydrogeologic characterization of the proposed mine site. Detailed local studies do not necessarily follow regional studies, components of both programs may be conducted concurrently. The preliminary determination of site specific hydrogeological conditions during initial exploration programs is often a cost effective means toward hydrogeological site investigation.
Table 1. Components of a Hydrogeological Site Characterization Program
Regional Study
(after Piteau Associates, 1991)

<table>
<thead>
<tr>
<th>STUDY AREA</th>
<th>CHARACTERISTICS</th>
<th>IMPORTANCE</th>
<th>INFORMATION SOURCES</th>
<th>PRELIMINARY STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiography, Geomorphology and Surficial Geology of Drainage Basin</td>
<td>site location, topography, landforms, soil types and distribution, depth to bedrock, size of catchment basin, groundwater divides, regional hydrogeology, recharge zones, discharge zones</td>
<td>helps determine expected hydrogeological conditions within the basin, i.e. gradients, recharge and discharge zones, hydrogeological character of soils based on landform, determine locations of components of the regional system</td>
<td>topographic maps, air photos, surficial geology maps, review of exploration drill logs</td>
<td>air photo interpretation, terrain analysis</td>
</tr>
<tr>
<td>Climate</td>
<td>precipitation (snowfall and rain), temperature, evaporation, transpiration, spring freshet</td>
<td>helps determine overall water balance for basin, assist in assessing seasonal variations in runoff, recharge and discharge</td>
<td>climatological station records</td>
<td>review of climatological data</td>
</tr>
<tr>
<td>Surface Hydrology</td>
<td>location of surface water bodies, infiltration capacity of soils</td>
<td>overall water balance, constant head boundaries</td>
<td>topographic maps, air photos, water license records</td>
<td>review of available data</td>
</tr>
<tr>
<td>Bedrock Geology</td>
<td>bedrock units, structural geology, grouping of hydrostratigraphic units, presence of confined and unconfined aquifers</td>
<td>hydraulic conductivity of individual units, anisotropy of bedrock, relationship to recharge and discharge zones</td>
<td>topographic maps and air photos, bedrock geology maps and open file reports, exploration drill logs, reports, regional geological studies</td>
<td>air photo interpretation, review of geological reconnaissance data from geological exploration, review of exploration drill hole logs</td>
</tr>
</tbody>
</table>
Table 2. Components of a Hydrogeological Site Characterization Program

Site Study

(after Piteau Associates, 1991)

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<th>INFORMATION SOURCES</th>
<th>PRELIMINARY STUDIES (Regional Data)</th>
<th>SITE STUDIES</th>
</tr>
</thead>
</table>
| Physiography and Geomorphology of Site | - landforms  
- slope grades  
- soil types  
- topography                                 | - landform type relates to soil types and hence expected hydrogeological parameters  
- unconfined aquifers are topographically controlled | - topographic maps  
- air photos  
- surficial geology maps  
- field studies                                 | - air photo interpretation, terrain analysis  
- ground reconnaissance, terrain mapping          | - photogrammetric mapping  
- ground surveys                                   |
| Site Surface Hydrology      | - location local surface water bodies  
- infiltration characteristics of soils and site components (waste dumps, tailings) | - run-off vs infiltration on the site  
- overall water balance  
- constant head boundaries  
- discharge areas                                   | - topographic maps  
- air photos  
- field studies                                 | - ground reconnaissance, stream mapping  
- stream flow measurements                          | - ground surveys  
- infiltration tests                                 |
| Bedrock Geology             | - bedrock units  
- structural geology  
- hydrostratigraphic units  
- confined and unconfined aquifers  
- lithology and structure                         | - relationship to recharge and discharge zones  
- the effect of fracturing on hydraulic conductivity  
- relationship to hydrogeology                      | - topographic maps and air photos  
- bedrock geology maps and open file reports  
- exploration drill logs, reports  
- field studies                                 | - air photo interpretation  
- geological reconnaissance  
- and mapping during exploration                    | - exploration drilling  
- test pitting and trenching                         |
| Quaternary Geology          | - soil types and distribution  
- soil stratigraphy  
- depth to bedrock  
- presence of confined and unconfined aquifers   | - needed in analysis of flow conditions and construction of conceptual model  
- needed in numerical model                          | - topographic maps  
- air photos  
- surficial geology maps  
- exploration drill logs  
- field studies                                 | - air photo interpretation  
- geological reconnaissance  
- and mapping during exploration                    | - test pitting and trenching  
- borehole drilling  
- geophysics                                         |
| Hydrogeologic Regime        | - depth to water table throughout site  
- potentiometric elevations  
- geometry of water table  
- hor. and vert. gradients                         | - needed in analysis of flow conditions and construction of conceptual model  
- needed in numerical model                          | - piezometer monitoring data  
- location of streams and standing water             | - location of streams and standing water             | - installation of piezometers and wells  
- monitoring of piezometers and wells                   |
| Flow Parameters             | - h/g flow parameter  
- hydraulic conductivity  
- porosity  
- specific storage  
- specific yield                                   | - needed in construction of conceptual model and analysis of flow conditions  
- needed in numerical model                          | - soil or rock type                                   | - first approximation based on soil or rock type   | - in situ testing (pump tests, slug and rising head tests) |
A general knowledge of the importance of hydrogeology as a controlling factor in the development of ARD at the site and the scale of the hydrogeological investigation required must be assessed prior to the design of the program. In the case of developing sites, the hydrogeological site characterization may also be conducted within the regulatory approval framework with increasing degrees of characterization being undertaken with greater amounts of mine development.

MOUNT WASHINGTON - A CASE STUDY OF THE IMPORTANCE OF HYDROGEOLOGY

Acid rock drainage from the Mt. Washington Copper Mine, closed in 1967, was suspected to be the cause of declining fish stocks in the Tsolum River in the late 1970's. Work by federal and provincial governmental agencies in the mid-1980's confirmed that the mine site was the source of elevated copper concentrations found in the river (i.e. Erickson and Deniseger, 1987).

The abandoned Mt. Washington Copper Mine is located approximately 25 km West of Courtenay on Vancouver Island on the northwest flank of a north-south trending ridge, 1.5 km north of the summit of Mount Washington (see Figure 3). Copper ore was mined from two pits between 1964 and 1967. The North Pit appears to be the only one of the two producing significant levels of acid rock drainage.

Figure 2. The Mount Washington Mine Site.
Site Characterization

Climate and Precipitation

There are extreme seasonal variations in precipitation at the site. After a relatively dry summer, heavy rains fall on the mine site through the fall. Up to 6 m of snow falls on the site during the winter months with snow often remaining on the site in June. A total of 3,800 mm is suggested as a reasonable estimate of the upper range of annual precipitation (Senes Consultants, 1993).

Site Topography and Surface Hydrology

The North Pit, covering an area of 3 hectares, comprises a partially covered pit area of mineralized bedrock, and East (0.75 ha) and West (0.30 ha) covered waste rock dumps. A smaller waste rock dump is located within the pit south of the West Waste Rock Dump. The pit area and East Waste Rock Dump are located in a slight depression as a result of mining activities. The West Waste Rock Dump is located on the convex shoulder of the ridge (see Figure 3). Surface drainage and groundwater discharge from most of the pit area sources the northward flowing Pyrrhotite Creek.

A diversion ditch located along the periphery of the pit, directs surface run-off from the portion of the ridge uphill of the pit, west of the West Waste Rock Dump, into a tributary of Piggott Creek. The elevated boundary between the North and South Pits results in surface water in the South Pit draining towards the McKay Creek drainage.

Geology

The abandoned Mount Washington Mine is a porphyry copper type deposit (Kwong, 1991). The gently southward dipping ore body is structurally controlled and confined to fracture and breccia zones along the contact of Tertiary porphyritic diorite and Nanaimo group argillites.

Metallic sulfides in the North Pit, occurring mainly as fracture filling material associated with quartz, include chalcopyrite, pyrite with minor amounts of pyrrhotite, marcasite, arsenopyrite, molybdenite, realgar, bomite and sphalerite. Pervasive small scale fracturing occurs throughout the ore body, although it is sometimes difficult to differentiate natural fracturing and that caused by mining activities. Large scale, subhorizontal fracture zones are also evident. Fracture distribution is not well known, but the small scale fracturing is thought to extend to a depth of approximately 10m (Golder Associates, 1990). The brecciated ore material is also noted to be locally vuggy with dissolution cavities.


Hydrogeology

The initial ARD abatement studies did not investigate groundwater conditions on the site in detail (Steffen, Robertson and Kirsten, 1987). Subsequent work determined that a perched water table exists on the site and that it contributes greatly to ARD generation as will be discussed.

A piezometer installation program carried out in 1989 (Golder Associates, 1990) concluded that: 1) a shallow water table was present across the site and that the water table elevation fluctuated widely with the onset of fall rains; 2) hydraulic conductivities were high in the upper fractured bedrock within the pit area and in the large scale fractures intersected by bore holes; and 3) background (upgradient) dissolved copper levels were low and the pit area contributed a large degree of the total copper loading compared to that of the waste dump during fall rains.

Potentiometric Surface

A shallow water table is developed on the site within the fractured bedrock. The potentiometric surface is topographically controlled, ranging from one to seven meters below the ground surface when measured in November 1989 (Golder Associates, 1990). The water table elevation varies seasonally due to recharge associated with fall rains and spring snow melt. Maximum fluctuations in the water table between 1991 and 1993 ranged from 0.6 to 1.75 m (Galbraith, 1994). The potentiometric surface of the regional water table is not known and it is unknown if it affects groundwater conditions at the site.

Artesian conditions are reported to exist in exploration drill hole EXP2 located at the south end of the North Pit hole following the spring freshet until mid to late summer (Galbraith, 1991). It is not known if the drill hole reaches the regional water table. The flow most likely indicates that the bore hole intersects one of the large scale fractures or a confined aquifer within Naniamo group sediments present in the area. This distinction might have important implications to the implementation of control strategies to minimize ARD migration.

Groundwater below the site is recharged through the infiltration of rainfall and snow melt across the site. The water table along the slope up hill of the site is also recharged by infiltrating rain and snow melt. Groundwater beneath this 6 to 7 ha area (see Figure 3) is expected to flow down gradient toward the North Pit.

Groundwater discharge areas in the form of seeps occur across the mine site. Groundwater discharge is high at the toe of the East Waste Rock Dump due to the convex shape of the mine site and discharge occurring into the base of the dump. Discharge also occurs at breaks in slope within the pit and is noted to
locally infiltrate into bedrock of high hydraulic conductivity. Groundwater discharge in the North Pit varies seasonally based on infiltration volumes and hence groundwater flux volumes. Continuous discharge through the summer was noted at the toe of the East Waste Rock Dump (Galbraith, 1991). Discharge from the head wall of the pit appears to be associated with localized large-scale, subhorizontal fracturing.

**Hydraulic Conductivity**

Hydraulic conductivities are highest ($10^{-4}$ to $10^{-5}$ m/s) in the compacted waste/shattered bedrock unit overlying bedrock in the pit. The hydraulic conductivity of the in-situ rock in the pit area ($4 \times 10^{-8}$ to $7 \times 10^{-6}$ m/s) is a function of the two previously mentioned fracture regimes and secondary dissolution. Competent bedrock is estimated to underlie the site at a depth of about 10m (Golder Associates, 1990).

The high hydraulic conductivity of large scale fractures ($10^{-4}$ m/s) may exert disproportionate control over the hydrogeologic regime. Where influenced by fractures, the groundwater flow is expected to be variable and difficult to predict.

**Site Groundwater Flow Conditions**

Groundwater modeling has been conducted by a graduate student group at UBC (unpublished) to try to determine the amount of inflow of groundwater from the up slope area into the pit. The contribution to flow of the large-scale fractures was not included in the model. The modeling confirmed that the majority of inflow was in the compacted waste/fractured bedrock zone, and that discharge occurs along the upper bench and portions of the headwall.

**Hydrogeological Controls on Acid Generation and Copper Transport**

Work by Kwong and Ferguson (1990) and Kwong (1992) identified a two step process linking acid rock drainage generation and metals transport to the seasonal variation in the water table. The process involves: 1) mineral/water interactions in summer and winter resulting in the generation of acidic and concentrated solutions located in pore spaces, fractures and as films adhering to mineral grains as well as the precipitation of soluble secondary copper minerals (malachite, chalcoalumite, brochontite), and 2) the flushing of solutions and the dissolution of the soluble secondary minerals during the spring freshet and fall rains when concentrated solutions are transported as surface run-off and through groundwater flow.

The described process is inexorably tied to seasonal variations in the water table. Lower groundwater elevations during the summer allow the production of low pH/copper rich solution and soluble precipitates and the higher groundwater fluxes in the spring and fall allow these to be flushed and transported.
Critical Hydrogeological Factors at Mount Washington

Prior to further remedial action several hydrogeological factors must be considered including:

1. The flushing and transport of ARD at the Mount Washington mine is partially tied to seasonal fluctuations in the water table elevation across the North Pit. Any reclamation strategy must recognize and address this process.

2. Groundwater elevations within the pit area and in the East Waste Rock Dump are a function of groundwater flow into these areas as well as the infiltration of precipitation. Any reclamation strategy must limit not only surface infiltration but limit the inflow of groundwater to the site.

3. The East Waste Rock Dump is located in a groundwater discharge zone. Groundwater will continue to be supplied to the base of the dump and ARD flushing and transport can be expected to continue within the dump.

SUMMARY AND CONCLUSIONS

Groundwater movement through and beneath ARD generating material is a primary pathway for contaminant migration. Acidic drainage might be transported away from the site of production through the flushing of groundwater flow. A site specific understanding of the role of groundwater in ARD flushing and transport is, therefore, a prerequisite to the understanding and prediction of the migration of acid drainage and the design of reclamation measures.

The importance of groundwater in ARD flushing and transport is demonstrated at the Mount Washington mine site. Initial reclamation measures have not been successful due to a lack of understanding of the role of groundwater across the site. Prior to further reclamation at Mount Washington, the role of groundwater must be recognized and further hydrogeological site characterization conducted. The distribution of fracture-controlled hydraulic conductivity must be further determined in order to understand the flow regime at the site. Artesian conditions must be examined in order to determine the role in ARD migration of any present confined aquifers. Further work must also be conducted to determine if regional groundwater flow influences conditions on site.

Any selected remedial options must be assessed with respect to the hydrogeological regime on the site. The preferred option will involve the covering of ARD generating rocks and barriers to groundwater flow to the North Pit and East Waste Rock Dump.
REFERENCES


