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GROUNDWATER QUALITY EVALUATIONS OF MINES

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ABSTRACT

Groundwater quality is an aspect of mine reclamation that is now receiving increased attention. The potential impact of mines on groundwater quality can be estimated by considering: mine water sources; groundwater flowpaths; waste characteristics; groundwater geochemistry, and environmental impacts. Primary groundwater flowpaths are within the more permeable geologic materials. These flowpaths can transport a significant mass of contaminants even though they generally comprise a small proportion of the materials. Impacts include potential degradation of water quality in local aquifers, lakes and streams.

Groundwater assessments can be carried out in four phases. Phase I consists of a review of existing data that are used to develop a preliminary hydrogeologic interpretation and define a Phase II field program. The preliminary interpretation is verified and a groundwater monitoring network is installed during the field program. The Phase I and Phase II data are amalgamated into a Phase III report, which documents the analysis and presents estimates of future impacts. Mine personnel, in Phase IV, collect and compile monitoring data that can be used to check the model estimates. In this manner, potential environmental liabilities are identified and the costs of remediation and/or mitigation are minimized.

INTRODUCTION

Groundwater quality is an aspect of mine reclamation that is now receiving increased attention. Regulations that will follow from the planned British Columbia groundwater legislation will bring groundwater more to the forefront in coming years.

A mine's objectives with respect to reclamation include:

- maintaining profitability;
- protecting the environment; and
- minimizing future liabilities and meet future regulatory requirements.

Unforeseen environmental liabilities can affect a mine's long-term profitability. A seemingly large investment now can prevent larger expenditures that might otherwise be required in the future to remediate undetected impacts.

An assessment of environmental risk includes a characterization of potential contaminant sources, groundwater flowpaths and discharge environments. As with all subsurface characterizations, some uncertainty is associated with interpretations of groundwater regimes. Problems typically result from conditions that were not anticipated. Therefore, quality control measures must be applied during groundwater assessments. A phased approach to groundwater assessments minimizes the quantity of unproductive data and clearly defines the data requirements. High risk elements can be identified and thoroughly investigated.

MINE WATER SOURCES AND FLOWPATHS

Tailings Management options include a variety of disposal methods from ponds through dry stacking. Mill reagents, heavy metals and weathering products that are resident in the tailings pore water can enter the groundwater system. If the tailings generate acid, the concentrations of some solutes will increase.

Valleys are often the most suitable sites for tailings storage. Valley bottoms can be infilled with glacial, alluvial or colluvial deposits, which can be relatively permeable. Tailings water can migrate downward into a permeable deposit through fractures or discontinuities in a low-permeability layer. Figure 1 illustrates a typical groundwater flowpath for water that exfiltrates from a tailings pond.

Waste Rock Waste rock dumps and ore stockpiles are also potential sources of heavy metals and other solutes. The main concerns are the residual nitrates from blasting and the weathering products of the freshly exposed rock. In some cases, waste rock generates acid water.

Waste rock dumps and ore stockpiles are often sited adjacent to the mine on native overburden deposits. A large proportion of the water that infiltrates into a waste rock dump usually runs off the dump foundation and can be collected in perimeter ditches. A significant proportion of the water, however, can infiltrate into the dump foundation. Even waste dumps that are founded on glacial till can lose a significant amount of water to the groundwater system through the more permeable flowpaths in the till. Figure 2 presents a section through a waste rock dump that illustrates typical groundwater flowpaths.

General Waste Most mines have waste disposal sites that contain mixed wastes, including reagent containers, lubricant containers, solvent containers and mill filters. Current disposal practices often include washing of spent containers. Infiltration through the disposal site can leach metals or reagents from the waste into the groundwater system.

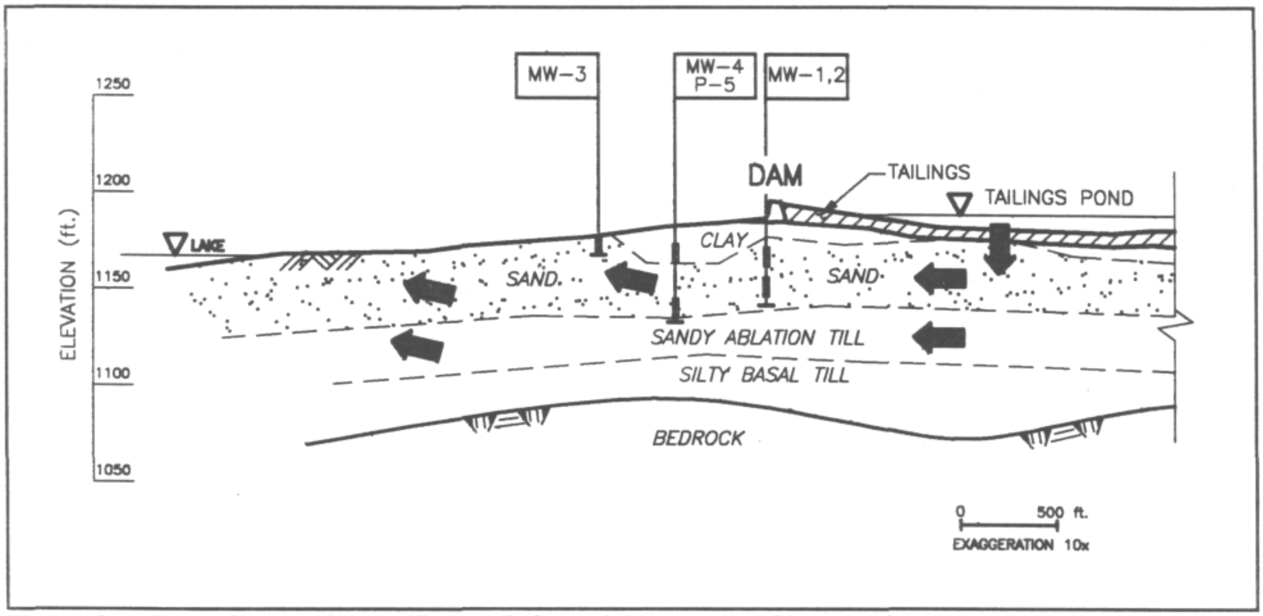

Figure 1 - Typical groundwater flowpath for tailings water exfiltrating from a tailings pond.

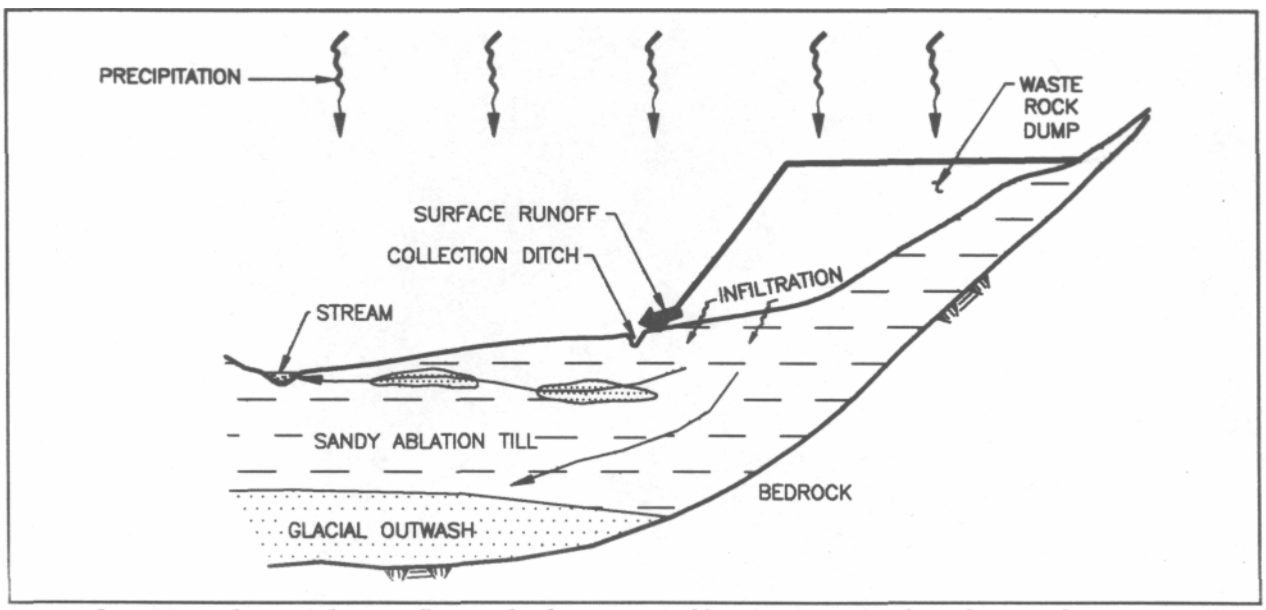

Figure 2 - Typical groundwater flowpaths for water infiltrating into the foundation of a waste rock dump.

Reagents. Fuels and Mine Drainage Reagents and fuels are often stored in the plantsite area. Accidental spills or past material handling practices can lead to groundwater contamination. Spills that occur are generally collected in ditches but exfiltration from the ditches can enter the groundwater system.

Drainage from the mine workings constitutes a large proportion of the site water-balance at many mines. Therefore, the quality and discharge point of the mine water are also key considerations.

HYDROGEOCHEMISTRY

Hydrogeochemical processes influence the mobility of solutes in groundwater. These processes include precipitation/dissolution and adsorption/desorption. Table 1 summarizes the controls on these processes and their effects on heavy metal and cyanide mobility.

Table 1 - Summary of Geochemical Controls on Contaminant Mobility

PROCESS	CONTROL	MEASURABLE PARAMETER	EFFECT ON MOBILITY
Precipitation/ Dissolution	Oxidizing capacity	Redox potential	· Heavy metals generally less mobile under oxidizing conditions.
	Acidity	pH	· Metals less mobile under neutral to alkaline pH. · CN less mobile under acidic pH.
	Aquifer mineralogy	Relative concentration of: · H_2CO_3, HCO_3^-, CO_3^{2-}, CO_2 · H_2S, HS^-, S^{2-}, SO_4^{2-} · Cl^- · F^- · NO_3^-, NO_2^-, NH_3	· Heavy metals form complexes that are generally more mobile than the free metal ions. · Large concentrations of these inorganic solutes generally lead to a higher degree of complexation.
Adsorption/ Desorption	Clay	Hydrometer analysis	· Significantly reduces mobility of cationic solutes below solubility constraints.
	Organics	Total organic carbon	
	Hydrous oxides	Redox potential and pH for estimation of thermodynamic stability.	

Redox potential is a measure of the oxidizing capacity of the groundwater. The redox conditions control the oxidation state of the solutes, which in turn influences their solubility. Heavy metals, for example, are generally more soluble and, therefore, more mobile in reducing conditions than in oxidizing conditions. Native groundwater environments are generally reducing, but oxidizing conditions can be created by mining activities causing increased recharge rates.

The buffering capacity of the receiving groundwater and the pH of the infiltrating mine water also have a strong influence on solute mobility. Metals generally have high mobility only at low pH. Cyanide mobility, on the other hand, tends to be higher at high pH.

Aquifer mineralogy can have a strong effect on solute transport. Carbonate in aquifer materials, for example, will tend to increase the pH of any acid mine water and cause the metals to precipitate. Sulphur, inorganic carbon, chloride, fluoride and nitrate ligands can form metal complexes, which have greater mobility than the free heavy metal ions. Clay minerals, organics and hydrous oxides in aquifers will tend to retard the advance of contaminants because of their adsorption capacity.

GROUNDWATER ASSESSMENT METHODOLOGY

Information that is relevant to a qualitative groundwater risk assessment is available at most mines. Available data are reviewed to develop a preliminary interpretation and focus available funding on the most significant mine water sources and groundwater flowpaths. The data review is generally followed by a field program, data analysis and monitoring program. This phased approach to groundwater assessments facilitates cost control and enhances technical quality.

Phase I: Data Review

The available data are examined for evidence or inference of potential for groundwater contamination. The presence of high risk mine water sources, significant groundwater flowpaths and/or sensitive receiving environments indicates a need for further investigation and characterization. A preliminary interpretation is developed and investigations are proposed to test or verify the interpretation. A groundwater monitoring network is also proposed to take advantage of the equipment that is mobilized for the site investigation. Table 2 summarizes the categories of data that are useful in forming a preliminary interpretation of groundwater conditions at a mine. The data are usually compiled as part of a site visit and in consultation with mine personnel.

Phase II: Field Program

At the conclusion of the data review, a preliminary interpretation will have been formed regarding the mine water recharge sources, groundwater flowpaths and groundwater discharge patterns. A field program that collects additional data on background conditions, mine waste characteristics and groundwater flowpaths is generally required to verify the interpretation and to install monitoring. The field program is adjusted as it progresses to accommodate new data. Table 3 summarizes the main activities of the field program. Quality control documentation is required for all field activities.

Surface activities are a key component of the site investigation because a great deal can be learned about mine water recharge mechanisms and rates and groundwater discharge patterns and rates. The surface activities are often the most cost-effective part of the investigation.

Cleanliness is a key issue in groundwater monitoring work. Drilling techniques that introduce drilling additives into the ground do not support the program objective, which is to obtain groundwater samples that will give a clear indication of the groundwater chemistry. Monitoring wells must be installed so that the groundwater samples are extracted from an identifiable zone with a minimum of disturbance to the groundwater chemistry. Several guidelines for materials are recommended, as summarized in Table 4. Quality control data must be collected for all installations.

Because the usefulness of groundwater chemistry data depends strongly on low suspended solids content, the monitoring wells require development to clean and stabilize the filter pack. The main well development activities are surging, jetting, and pumping. Figure 3 illustrates the principle of well development.

Phase HI: Analysis and Reporting

A hydrogeologic analysis includes an assessment of data quality, and interpolation and extrapolation of the database. The data that were collected during Phases I and II are plotted with time, in section and in plan. The data plots are examined for correlations with mine activities, precipitation, streamflows and any other known conditions near the mine. The data are also examined for corroboration. For example, water sample data should be consistent or behave as expected from one sampling period to the next. Data that correlate and corroborate are usually of adequate quality to define site conditions.

An important corroboration is the "match" of the site data with accepted hydrogeologic theory. That is, interpolation and extrapolation of the data set are reasonable if the observed conditions can be modelled with reasonable input parameters. Hydraulic and geochemical data from across the study area and through time are required to adequately match a model to site conditions. The groundwater model characterizes: recharge mechanisms and rates; transmission characteristics; and discharge mechanisms and rates.

Table 2 - Summary of Data Categories

DATA CATEGORY	COMMENTS
TOPOGRAPHY	
present mine topography	plan area of waste dumps and tailings pond(s), pond elevations, ditch layout, stream gradients
pre-mine topography	topography under waste dumps and tailings ponds
regional topography	regional recharge and discharge patterns, catchment areas
EXPLORATION	
background geology reports	overburden thickness and types, relative permeability of bedrock and overburden
air photos	springs, overburden thickness, bedrock structure
drill hole logs	overburden thickness, bedrock topography
geophysics	overburden thickness, water table depth, bedrock topography, plume detection
soil geochemistry	background chemistry
HYDROGEOLOGY	
piezometric levels	flow directions, recharge rates and discharge rates
groundwater chemistry	background chemistry, plume detection, mass transport characteristics
aquifer mineralogy	mass transport characteristics
response tests	hydraulic conductivity
water well inventory	potential impact
drill hole logs	aquifer and aquitard characteristics
HYDROLOGY	
streamflows	baseflow estimate for groundwater balance
precipitation	infiltration estimate for groundwater balance
surface water chemistry	background and downstream receiving water chemistry
evapotranspiration	infiltration estimate for groundwater balance
OPERATIONS	
tailings characteristics	source chemistry
waste rock characteristics	source chemistry
mill reagents	source chemistry
effluent water chemistry	source chemistry
timing of mine operations	correlate with hydrogeologic and hydrologic data
pumping and discharge records	water balance

Table 3 - Summary of Field Program Activities

ACTIVITY	DETAILS
SURFACE	
surface mapping	· seep locations and flow rates · infiltration characteristics
surface water quality	· ponds, seeps, streams · background and downstream samples
surface geophysics	· water table depth · aquifer dimensions and location · sub-surface investigation targets
SUB-SURFACE	
test pitting	· near surface geology · water table depth · water quality
drilling, soil sampling and monitoring well installation	· hydrogeologic characterization · water sampling
borehole geophysics	· detailed stratigraphy
well response testing	· aquifer hydraulic conductivity
groundwater sampling and testing	· conventional monitoring wells · sub-surface probes · background and downstream samples
waste characterization	· source chemistry

Table 4 - Summary of Monitoring Well Materials

MONITORING WELL COMPONENT	SPECIFICATION	DESIGN OBJECTIVE
Monitoring Zone Backfill	Silica Sand · clean, rounded	· chemically inert · sized to form an effective filter
Monitoring Zone Seal	Bentonite · chips or grout	· isolate the sampling zone from vertical groundwater seepage along the drill hole · protect the sampling zone from cement grout contamination
Annular Backfill	Cement Grout · viscous, non-shrinking	· prevent vertical seepage along the drill hole · minimize grout migration into the formation
Monitoring Well Screen and Riser	2" PVC for metal mines · flush threaded · O-rings · schedule 80	· chemically inert · screen sized to retain the silica sand backfill · minimal disturbance of flow regime · large enough to accommodate a wide variety of sampling tools · small enough to minimize disturbance to the flow regime

Each component of the groundwater model requires calculations, which must be based on sound hydrogeological and hydrogeochemical principles. The calculation method is chosen on the basis of model complexity, which is determined by the quality and depth of the database, and the required level of understanding. Preliminary assessments are usually carried out with hand calculations and represented in a fashion similar to Figure 4. Figure 4 summarizes the water balance and flowpaths of a simple groundwater model. The model can be updated and expanded as the database grows. A similar presentation can be prepared for mass balance. Computer analysis is generally reserved for complex models that are based on an appropriate database.

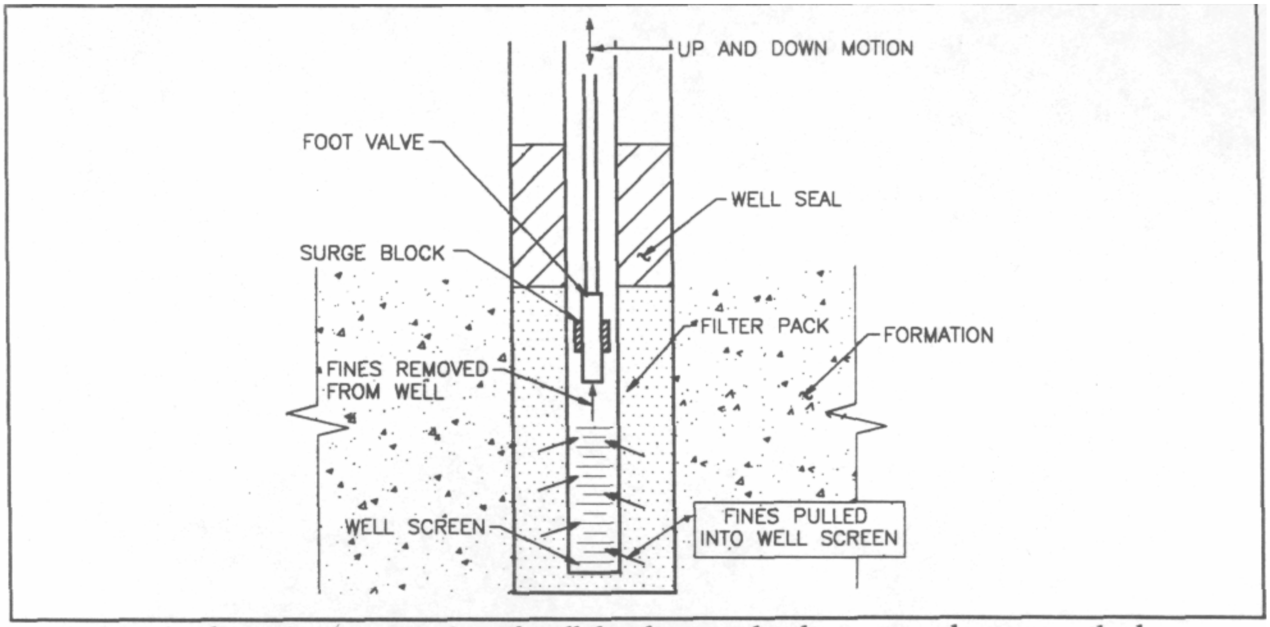

Figure 3 - A schematic representation of well development by the surge and pump method.

After the data have been correlated and corroborated, a groundwater model is developed to extrapolate the existing data and estimate potential future impacts. Depending on the results of the extrapolation, a suitable monitoring program is designed and any additional data requirements are defined. A report summarizes the data sources, the data record, a description of the hydrogeologic and hydrogeochemical interpretation, the implications of the interpretation, and the recommended monitoring program.

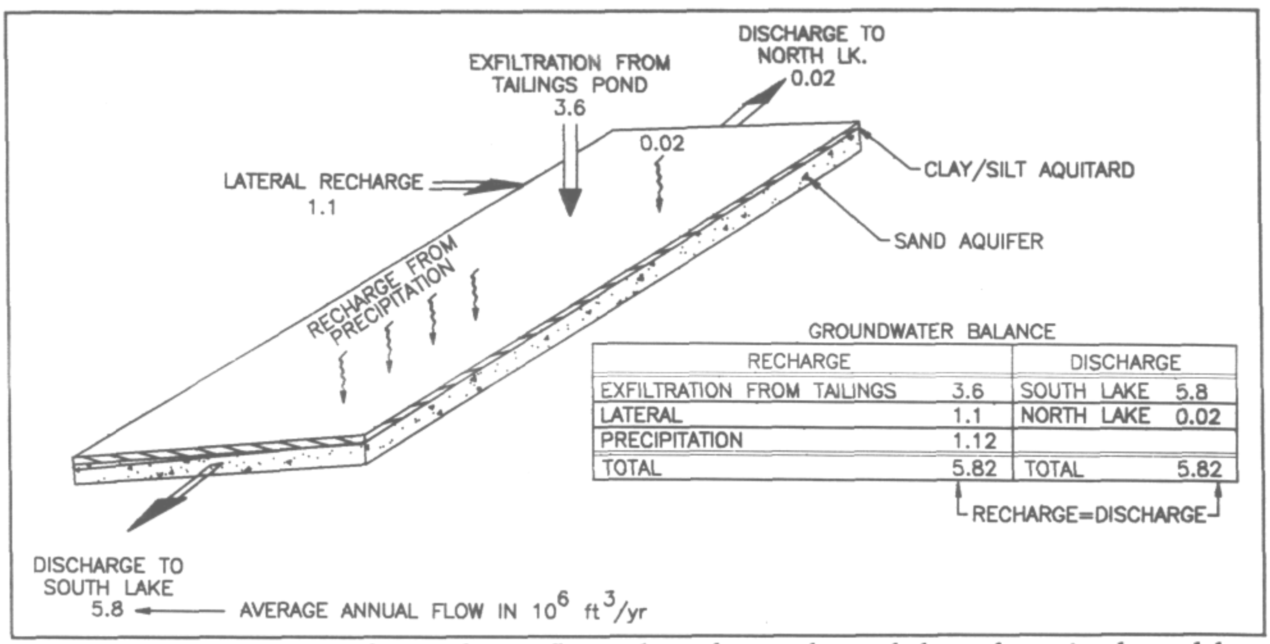

Figure 4 - Representation of groundwater flowpaths and groundwater balance for a simple model.

Phase IV: Monitoring Program and Data Management

A monitoring program consists of collection and analysis of samples at prescribed frequencies from selected locations.

Special measures are required to obtain groundwater samples of sufficient quality for a meaningful interpretation. Unlike surface water samples, groundwater samples are transferred into an environment that is different from their native environment. Changes that affect the groundwater sample chemistry upon extraction include temperature shifts, pressure decrease and oxygenation. Therefore, some chemistry parameters must be recorded in the field at the time of sampling because they are prone to change within a very short time. These parameters include temperature, pH, conductivity and redox potential. These field parameters are best measured in a flow-through cell.

Another important component of groundwater sampling is cleanliness of sampling equipment. Cleanliness is central to a sound groundwater chemistry database because significant contamination occurs at parts per million levels. A sampling and handling plan is required to ensure that adequate quality control measures are implemented during groundwater sampling. Table 5 summarizes the primary elements of a sampling and handling plan.

Table 5 - Elements of a Sampling and Handling Plan

ELEMENT	DETAILS	REQUIREMENTS
SAMPLING TECHNIQUE	· sampling device · intake position · pumping rate · purge volume · decontamination measures	· minimal and reproducible effect on sample chemistry · no cross contamination · no external contamination · direct filtration · closed system for field parameter measurement
FIELD MEASUREMENTS	· meter quality · flow through cell · meter calibration	· meters calibrated to standards · laboratory grade · measurements made under conditions that are close to natural environment
QUALITY CONTROL DATA	· equipment tests · trip blank · equipment blank · equipment spike · replicate samples	· documents instrument accuracy and reproducibility · documents effects of sampling environment and sampling technique on sample chemistry · documents decontamination and sampling procedures

A computer database and computer graphics are the most efficient tools for managing groundwater data. The database facilitates swift information retrieval and the graphics synthesize large quantities of data into readable "pictures" that reveal patterns and trends. The chemistry data evaluation generally consists of two steps:

- data quality assessment; and
- groundwater chemistry assessment.

Table 6 summarizes the elements of a data quality assessment.

The quality of the groundwater chemistry data is evaluated on the basis of data consistency and isolation of external influences. For example, high suspended solids in groundwater samples can lead to variable and unreliable groundwater chemistry results. A comparison of the pH, redox potential, temperature and conductivity that were measured in the field with those that were measured in the lab will reveal shifts that have occurred. The significance of any shifts in these parameters requires an evaluation.

Table 6 - Summary of Data Quality Assessment

DATA QUALITY PARAMETER	POSSIBLE EVALUATION TECHNIQUE
suspended solids	· plot suspended solids vs. solute concentrations to check for correlation · ideally less than 20 mg/ℓ
total vs. dissolved metals	· plot ratio of total:dissolved on a bar chart, should be greater than one
consistency within a well	· plot mean with standard deviation bars for monthly samples in a single well · account for variations
trip blank	· compare chemistry to original water, account for variations
equipment blank	· compare chemistry to original water, account for variations
equipment spike	· compare chemistry to original water, account for variations
charge balance	· confirm that laboratory analysis gives a charge balance
correlation between specific conductance and total dissolved solids	· confirm correlation or account for absence of correlation
correlation between total dissolved solids and sum of individual analyses	· confirm correlation or account for absence of correlation

After the data quality has been established, the groundwater chemistry can be assessed. Table 7 summarizes the elements of a groundwater chemistry assessment.

Table 7 - Summary of Groundwater Chemistry Assessment

DATA	ASSESSMENT METHOD
WATER CHEMISTRY - tracers - contaminants	
spatial distribution · plan and section	· plot and contour water chemistry results on a hydrogeologic section and/or plan · plot normalized water chemistry results on a bar chart along groundwater flowpath
temporal variation	· plot time series of water chemistry · plot concentrations at successive times on a section and/or plan
WATER LEVELS	
spatial distribution · plan and section	· plot and contour water levels on a hydrogeologic section and plan
temporal variation	· plot time series of water levels and indicate any mining activities that may account for water level variations · plot and contour water levels at successive times on a section and/or plan · plot monitoring well water levels against pond elevations, precipitation and/or stream stage

The groundwater chemistry assessment must consider both the presence of tracers and contaminants. Tracers are solutes such as sodium, nitrate and sulphate that travel relatively freely through the groundwater system and indicate the presence of mine water. The eventual arrival of a heavy metals plume, for example, can be indicated by a sulphate concentration that is significantly above background.

Figure 5 illustrates a plot of cyanide (contaminant) and sulphate (tracer) in several monitoring wells along a groundwater flowpath. The elevated cyanide and sulphate concentrations correlate with a near-by tailings impoundment. The cyanide data corroborate the sulphate data.

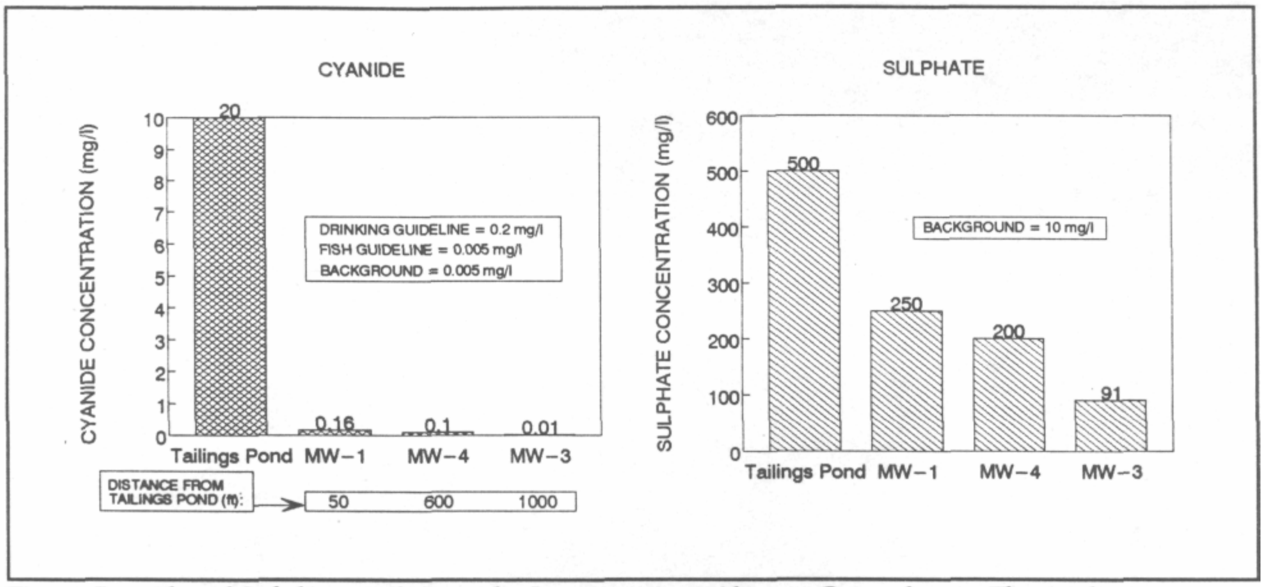

Figure 5 - Plot of Sulphate and Cyanide Concentrations Along a Groundwater Flowpath

The cyanide and sulphate concentrations in MW-1 and MW-4 are about 30 times and 20 times groundwater and background, respectively. The cyanide concentration in MW-3, however, is only about twice background, whereas, sulphate is about 10 times background. This indicates that geochemical processes may be retarding cyanide transport relative to sulphate transport. Geochemical processes probably also account for the relatively large drop in cyanide concentration between the tailings pond and MW-1.

SUMMARY

A groundwater quality assessment can be conducted in four phases. A model that can be used to estimate potential future impacts is developed in Phases I to III. Data that can be used to check and refine the groundwater model are collected during the Phase IV monitoring program. Quality control measures during all phases of data collection and analysis are required to ensure that the collected data are usable and to ensure that the model adequately represents site conditions. Groundwater quality assessments are required to protect mines from unforseen liabilities, protect the environment, and meet regulatory requirements.