PREVENTION OF ACID DRAINAGE FROM GOLD MINING IN THE WESTERN UNITED STATES AND IMPACTS ON WATER QUALITY

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ABSTRACT

Water quality regulations recently adopted by states in the western USA have increasingly stringent limitations on allowable changes in the quality of surface water and groundwater. The "nondegradation of water" provisions in state regulations require accurate predictions and control of the quantity and quality of acid mine water and strictly limit the entry of acid water into natural water systems. Long-term water quality impacts from mine waste rock, spent ore from heap leaching, tailings and open pits must be considered in design, operation and reclamation of proposed or expanded mining operations.

Acid-base testing, humidity cells, column testing and shake flask tests have been used with mixed success to predict the extent of acid water production. The types and forms of sulfide minerals present, bacterial catalysis of the sulfide oxidation reaction and configuration of the reclaimed facilities are all important elements in accurately predicting acid mine drainage.

A critical factor in prediction of acid mine impacts is a pathway and fate analysis which includes geochemical reactions with aquifer materials and dilution and dispersion of parameters in the leachate plume. Of particular concern is the production and transport of arsenic, metals and residual cyanide from mined areas. Evaluation of three major operating gold mines in the northwestern United States shows the relationship between production of acidic water, movement of this water in aquifers and impacts on groundwater and surface water. Column testing showed reduction in concentrations of most metals by 50 to over 90 percent during travel through aquifers. Clays and silt zones were very effective in adsorbing metals.

Operational control of water/rock reactions and reclamation design can significantly reduce or eliminate acid drainage. Soil cover, revegetation and slope are the major components that limit long-term acid drainage and metal contamination of surface water and groundwater. Compliance with water quality limits can be achieved only by design and operation of mining facilities to minimize the formation of acidic waters.

INTRODUCTION

A major increase in gold mining has occurred in the western United States in the past ten years and many additional mines are being developed or expanded. Some of the older mines and a number of the new developments will be in sulfide-bearing rocks. In response to increased mining, the western states have expanded their regulatory programs and have placed stringent controls on mining and ore processing. This increased regulatory concern requires accurate prediction and control of the quantity and quality of acid drainage and requires control of the entry of acid water into natural water systems.

Acid water predictive techniques must consider the quantitive interaction of sulfide-bearing rock with water in open pits, underground mines, waste rock dumps, leached ore heaps and tailings ponds both during and after mining. Design of these facilities to reduce or prevent acid drainage is significantly different for arid (evaporation exceeds precipitation) and wet (precipitation exceeds evaporation) climates. Both during and after mining, acid water emanating from the project site must not cause violations of state and federal water quality standards for surface water and groundwater at the designated compliance points.

CHARACTERISTICS AND PREDICTION OF ACID DRAINAGE

Acid drainage normally involves reaction of pyrite or other sulfide minerals with air and water and yields acidity, sulfate, iron and other metals. In western gold mines the acidic waters react with geological materials and many metals and other parameters are dissolved. These include:

Antimony
Arsenic
Barium
Beryllium
Cadmium
Chromium
Copper
Lead
Manganese
Mercury
Nickel
Selenium
Silver
Thallium
Zinc

The allowable concentrations of these parameters in surface water and groundwater are limited by state and federal regulations. In addition, other constituents of concern associated with acidic waters are acidity, sulfate, low pH and nitrogen compounds from rocks where blasting has occurred. If process waters are involved, such as in tailings ponds and leached heaps, other parameters of importance are sodium, chloride and cyanide. Typical quality characteristics of waters associated with northwestern USA gold mines are in Table 1.

Prediction of Acidity

Prediction of acid water is often based on observation and tests of springs, and streams in the proposed mining area and particularly water from old workings such as pits, adits or boreholes that may be present. A comparison with other mines with similar geological, mineralogical, and hydrological conditions also can be useful.

Table 1. Typical Acid Mine Water Characteristics from Gold Mines

Parameter	Gold mine Adit discharge Montana, USA	Gold mine Tailings pond seepage South Dakota, USA	Gold mine pit seepage Montana, USA
pH	3.0	3.10	2.5
Total Dissolved Solids	1530		1460
Acidity as $CaCO_3$	40.7		778
Sulfate (SO^4)	1110	625	910
Nitrate (NO_3)	0.21	2.09	<0.05
Ammonia	0.3	0.21	0.3
Arsenic (As)	0.007	0.1150	<0.005
Cadmium (Cd)	0.038	0.006	0.021
Copper (Cu)	6.84	3.37	27.8
Iron (Fe)	28.2	9.40	231
Lead (Pb)	<0.01	0.003	0.02
Manganese (Mn)	1.21	3.98	4.44
Mercury (Hg)	<0.005	0.001	<0.001
Nickel (Ni)	0.43	0.07	
Selenium (Se)	<0.005		
Silver (Ag)	<0.005	<0.0005	<0.00500
Zinc (Zn)	6.04	1.64	2.76

All concentrations are in mg/L except pH (standard units)

Another method to assess the potential for acidity is based on visual observation of sulfide mineralogy of samples from exploration boreholes or test excavations. Many geological, mineralogical and host rock conditions can affect the potential for acid drainage. In general, if sulfide minerals are less than 1% of the rock mass, acid water is unlikely; from 1 to 3% acid water may occur and over 3% acid water is likely.

Probably the most commonly used indicator of the potential for acidic drainage is acid-base balance testing [Smith et al., 1974]. In this procedure, the acid potential and base potential are determined separately. The acid potential is determined by measurement of total sulfur in a rock sample using a Leco furnace and sulfur analyzer. The acid potential is then calculated by assuming all of the sulfur is in the form of pyrite and is entirely converted to acidity. The resultant acid potential is reported as equivalent tons of $CaCO_3$ per 1,000 tons (ppt) of the rock. A major problem with this procedure is that it often overestimates the acidity if some sulfur species in the sample are not acid-generating, which is common in many rock types.

The neutralization potential of the sample is measured by its ability to neutralize a strong acid. An excess of hydrochloric acid is added to the sample and, after reaction, the excess acid is measured. This procedure measures neutralization potential but does not determine the pH that will occur after neutralization.

The net acid-base balance (also termed net neutralization potential) is determined by subtraction of the acid potential from the neutralization potential. Generally, a net acid-base balance of lower than -5 tons of $CaCO_3$ per 1,000 tons of rock is assumed to have the potential to generate acidity [Sobek, et al., 1978]. Actual acid water generation in rocks also is determined by the rates of acid production and neutralization reactions. If acid production is slow relative to neutralization, rock with net acid potential may not yield significant acidity. Conversely, rocks with net neutralization potentials have been found to generate acidic waters [Kleinmann, 1989].

Since acid-base testing does not assess relative rates of the neutralization and acidification processes, additional testing may be required to confirm the potential to generate acidity and to determine the rate of acid generation. A variety of tests have been developed to further define the potential for generation of acidity including the Soxhlet Test [Sullivan and Sobek, 1982], B.C. Confirmation Test [Bruynesteyn and Hackl, 1984], Shake flasks [Halbert et al., 1983], humidity cells [Caruccio et al., 1980] and column tests. These tests place the sample in contact with water and in some procedures the mixture is innoculated with Thiobacillus ferrooxidans bacteria to increase the acid producing reaction. Based on these tests, the acid production potential and comparative rates of reaction can be estimated. In addition, the test solutions can be analyzed for pH, acidity, sulfate, metals and other parameters to provide an estimate of water quality in the acidified water. None of these tests are considered "standard" and results of the tests require experience in interpretation for specific mine sites.

The following are two case studies from the northwestern United States. Acid drainage predictions were made and field results obtained for two open-pit gold mines in Montana and South Dakota. Both of these deposits are low grade disseminated deposits in igneous rocks that have intruded into sedimentary strata. Ore grade material generally contains from 1 to 5 mg/kg gold. Both of these mines recover gold using the cyanide heap leaching process.

Case 1 - Open-pit gold mine in Montana

Predictive methods for acid mine waters at this site included evaluation of drainage from an historic mine adit, acid-base balance and humidity cell tests. Water quality of discharge from a nearby historic adit is acidic (pH of 3) and contains high concentrations of metals (aluminum, copper, iron, manganese, nickel, and zinc) and sulfate. Results of acid-base balance potential testing is in Table 2. The observed high potential for development of acidic water from this deposit was supported by net acid-base balances for the majority of waste rock types of 4 to 168 ppt (parts per thousand) excess acidity. In contrast, excess acidities estimated by humidity cell tests were less than 5 ppt for all rock types. Most rock types had low to moderate neutralization potentials. The humidity cell results may represent the short-term test condition where acid produced is rapidly neutralized by the natural neutralization capacity of the rocks. These test results and observations of existing acid mine waters suggest that for these rocks, acid-base balance tests are a better predictor of long-term acid potential than humidity cells.

Table 2. Acid Prediction Results

		Acid-Base Balance Tests		
Rock Sample	Humidity Cell Acidity (ppt)	Acid Potential (ppt)	Neutralization Potential (ppt)	Net Acid-base Balance (ppt)
1	0.014	82.6	11	-71.6
2	0	38.9	35	- 3.9
3	0	47.6	35	-12.6
4	0.029	161.0	29	-132.0
5	0	107.6	30	-67.6
6	0	82.9	23	-59.9
7	2.39	111.2	<1	111.2
8	0.923	20.1	4	-16.1
9	0	176.1	8	-168.1
10	0.512	43.1	6	-37.1
11	0	87.0	9	-78.0
12	0	29.2	15	-14.2
13	0.546	5.8	16	+10.2
14	0.238	14.3	<1	-14.3
15	0.004	4.5	6	+ 1.5

Case 2 - Open-pit gold mine in South Dakota

Ore mineralization at this mine is characterized by gold, silver, and arsenic-bearing sulfide minerals including pyrite and arsenopyrite. Acid-base balances of waste rock and ore ranged from 0 to 30 ppt excess acidity indicating a potential for acid generation from some rock types.

The mining plan was then used to determine the amount of each rock type to be mined. The amount of each rock type was then multiplied by the net acidity of each rock to obtain a "weighted" net acid-base balance for each waste rock and ore type. The weighted net acid-base balance of waste and ore types was determined to be 7.8 ppt excess acidity indicating a potential for acid drainage from waste rock at this operation. Ore is agglomerated with 2 to 3 ppt portland cement to aid in the cyanide heap leach process. Because of the cement addition, leached ore will release alkalinity until the cement is leached from the spent ore and, at least initially, the spent ore will not be a source of acidity.

To estimate the water quality of waste rock leachate, column leach tests and Extraction Procedure Toxicity [U.S. EPA, 1985] tests of waste rock material were conducted to simulate reaction of waste rock with natural precipitation. Column tests were conducted in 61 cm. long plastic (PVC) columns filled with waste rock crushed to minus 10 mm particle size. This particle size is much finer than the mining waste rock which is about 0.1 to 0.5 meters in diameter. However, the finer particle size was used to increase water/rock contact and to accelerate leaching rates. Columns were leached with deionized water for 10 days and effluent waters were collected and analyzed for metals and major elements. Typical column leach results (Table 3) show waste rock column leachate contained less than detectable amounts of most metals and had near neutral pH. Low concentrations of iron and sulfate were generated in the waste rock columns, suggesting pyrite oxidation may occur in waste rock but at a slow rate relative to the duration of the column leach test.

Since we were unable to initiate substantial acid generation in the column leach test, an acid leach of waste rock was conducted using the Extraction Procedure Toxicity Method. This method was chosen for the acid leach due to its widespread acceptance by state and federal regulatory agencies as a standard test of metal leachability. This procedure consists of a 24-hour, agitated bottle roll of crushed rock (4.2 mm particle size) in an acetic acid solution buffered to a pH of 5. Typical Extraction Procedure Toxicity results for waste rock leachate are in Table 3. Surprisingly, concentrations of metals leached from waste rock by the Extraction Procedure Toxicity were lower than concentrations from the column leach test. This may indicate that while the Extraction Procedure Toxicity method is a more aggressive leach due to the more acidic leach solution, the longer contact time between rock and water in the column leach test causes more leaching.

Table 3. Predicted Water Composition

	Waste rock		Spent Ore		
Parameter	Column Leachate	Extraction Procedure Toxicity	Column Leachate	Bottle Roll Leachate	Wash Solution
pH	6.9		9.1	9.2	9.2
Sulfate	16		39		270
Cyanide-WAD			0.17	0.024	0.27
Arsenic (As)	0.019	0.006	0.22	0.06	0.23
Barium (Ba)	<0.2	0.6	<0.2		<0.1
Cadmium (Cd)	<0.001	<0.02	0.002		0.001
Chromium (Cr)	<0.02	<0.02	<0.02		<0.02
Copper (Cu)	<0.01		0.02	0.021	0.22
Iron (Fe)	0.13		0.24		<0.03
Lead (Pb)	0.01	<0.1	<0.01		<0.01
Manganese (Mn)	<0.02		<0.02		<0.02
Mercury (Hg)	<0.001	<0.001	<0.001	0.0003	0.0004
Nickel (Ni)	<0.03		<0.03	<0.005	<0.005
Selenium (Se)	<0.005	<0.005	<0.005		0.016
Silver (Ag)	<0.005	<0.02	<0.005	0.0007	0.014
Zinc (Zn)	<0.01		<0.01	0.02	0.01

Results of all analyses are in mg/L.

A comparison of column and bottle roll leach tests of spent ore with wash solution (leachate) from an actual neutralized spent ore heap are in Table 3. These tests show both column and bottle roll tests accurately predicted the pH of leachate, however, column tests more accurately predicted metal concentrations. In part this may be due to use of more representative cyanide concentrations in the column tests. Sulfate concentration in actual spent ore leachate was substantially higher than estimated by the column leach. This may due to the fact that sulfate is present in small amounts in portland cement which is used for agglomeration of the ore. Ore processing solutions are circulated in a closed system and no water is discharged, therefore soluble sulfate present in the ore or cement becomes concentrated in process water. Alternatively, some oxidation of pyrite may be occurring most probably due to the hydrogen peroxide rinse of the spent ore.

WATER QUALITY STANDARDS

The quality of groundwater and surface water is regulated by the EPA (United States Environmental Protection Agency) and by individual state governments. These quality standards are a significant constraint in mining and mineral processing projects and affect project design, operation and reclamation. Recent EPA regulations require that states adopt numeric water quality standards for toxic pollutants including water quality standards for both aquatic life and human health protection for specific priority pollutants [Federal Register, V.55 No. 74, April 17, 1990]. The EPA is proposing standards for states that fail to adopt the required numeric standards. As a result of federal regulations, the EPA "Goldbook" criteria [Water Quality Criteria for Water, EPA 440/5-86-001, 1986] are rapidly becoming standards for water quality in streams in the United States. These standards include both chronic and acute aquatic life criteria and human health criteria. The Goldbook criteria, when adopted as numeric standards, include some very stringent limits on many toxic substances as shown on Table 4. Limits on substances such as cadmium, mercury, lead and silver are not only stringent, but are lower than the analytical detection limit in nearly all laboratories. For example, the EPA human health criteria for arsenic at the 10^{-6} lifetime cancer risk level is 0.022 ug/L (EPA Goldbook, 1986) which is about two orders of magnitude below the laboratory detection limit for arsenic.

Generally, state regulations require that the quality of groundwater and surface water cannot be degraded to where it will become worse than shown in Table 4, either during operations or after mining is completed. As shown in Table 4, the maximum contaminant concentrations are very low particularly for the chronic aquatic criteria.

The question of where the water quality standards apply is also important. Most states are applying the groundwater quality standards at the outer edge of the area owned or controlled by the mine operator or in a "perimeter of pollution" which is the edge of a defined area peripheral to the mining and ore processing facilities. Surface water criteria are applied to any streams that receive water from the mining operation. In streams, a mixing zone is generally allowed, that is, the criteria only apply downstream of a linear segment of the stream where the natural stream waters have mixed with water discharging from the operation. Since nearly all existing and proposed mines in the northwestern United States are in or near drainages with perennial streams, the production of acid water and movement of this water into groundwater and surface water is a critical factor in design, operation and reclamation of mining properties.

PREDICTION OF WATER QUALITY IMPACTS

Prediction of water quality impacts requires an understanding of local geological and hydrological conditions, the estimated quantity and quality of discharge water from all mine facilities, and knowledge of the behaviour of contaminants in hydrological systems. Other factors

Table 4. EPA Goldbook Acute and Chronic Aquatic Criteria and Drinking Water Standards

Parameter	Chronic[1] Aquatic Criteria (mg/L)	Acute[2] Aquatic Criteria (mg/L)	Drinking Water (mg/L)
Antimony	1.6	1.6	NS
Arsenic III	0.19	0.36	0.05
Arsenic V	0.048	0.048	0.05
Barium	NS	NS	1.0
Beryllium	0.0053	0.13	NS
Cadmium *	0.0011	0.0039	0.010
Chromium III *	0.207	1.74	0.05
Chromium IV	0.011	0.016	0.05
Copper *	0.012	0.018	1.0
Cyanide	0.005	0.022	0.22
Iron	1	NS	0.3
Lead *	0.003	0.08	0.05
Manganese	NS	NS	0.05
Mercury	0.000012	0.0021	0.002
Nickel *	0.158	1.42	NS
Nitrate	NS	NS	10
Nitrite	0.06	NS	NS
pH	6.5 - 9.0	NS	5 - 9
Selenium	0.035	0.26	0.01
Silver *	0.00012	0.0041	0.05
Sulfide	0.002	0.002	NS
Thallium	0.040	1.4	NS
Zinc *	0.106	0.117	5.0

[1] Chronic toxicity effects may occur if 4-day average concentration of parameter exceeds criteria more than once every 3 years.

[2] Acute toxicity effects may occur if 1-hour average concentration of parameter exceeds criteria more than once every 3 years. Exceedance frequency of 3 years is U.S. EPA best scientific judgement of the average amount of time it will take an unstressed system to recover from a pollution event in which exposure exceeds the criteria.

[3] No criteria for As V, Sb, Be and Th - lowest observed effect level shown. Drinking water standard for arsenic and chromium are based on total concentration of all species.

* Criteria dependent on hardness - 100 mg/L hardness as $CaCO_3$ used in this table.

NS-No standard or criteria.

in predicting water quality impacts are identification of beneficial water uses, analysis of pathways for mine waters to reach and impact beneficial uses, and determination of geochemical attenuation of contaminants in groundwater and surface water. Both the flow and quality of water from mine-related facilities must be predicted for the operational and long-term post-mining period. These flows can be predicted as follows:

1) Tailings Ponds. Normal reclamation would include a 0.3 to 1 meter capillary break of coarse rock covered by 0.3 to 1 meter of soil and a vegetative cover is established. A plastic membrane liner also can be used between the rock cover and the soil to exclude water from the tailings, thus creating a composite liner. Such liners are not commonly used but will be increasingly used in the future particularly in wet climates. The flux of water through the liner and tailings can be predicted by numerous techniques. However, the HELP (Hydrological Evaluation of Landfill Performance) model, which is a two-dimensional, water budget model, that simulates water movement across, into and through landfills [Schroeder and others, 1988]. It predicts runoff, drainage and leachate that may result from operation of sanitary landfill. Although developed for landfills, it is increasingly being used for tailing ponds and other waste containment facilities. Various cover designs including soils, vegetation and special layers can be simulated. Other water balance models such as the Jensen-Haise [Jensen, 1983] and Blaney-Criddle [Jensen, 1983] can be used to estimate water flux into reclaimed tailing ponds.

2) Waste Rock and Leached Ore Heaps. Waste rock and leached ore heaps (heaps leached by cyanide to recover gold) generally are reclaimed by regrading to 2h:1v slopes or flatter, and are covered with 0.2 to 1.0 meters of soil and a vegetative cover established. There are no widely accepted techniques for prediction of water fluxes through these reclaimed facilities. The HELP model is limited to slopes of 30% or less but is being used to predict fluxes through waste rock and leached ore.

3) Mined Areas. Reclamation of open pits sometimes involves cover of pit bottoms and selected benches with 0.2 to 1 meter of soil and establishment of a vegetative cover. The flux of water through open pits can be predicted using many techniques however groundwater computer models are increasingly being used to predict water flux through reclaimed pits. Underground workings are a different situation and it often is difficult to predict the post-mining water in closed workings. A wide variation in underground mine configurations, tunnel plugs and rock permeability and fracture patterns results in the requirement for very site-specific prediction techniques. Again, groundwater models are increasingly being used to

predict the post-mining water flux through underground workings.

PATHWAY AND FATE ANALYSIS

The pathway analysis must consider both groundwater and surface water and normally involves a groundwater flow model based on measured and estimated aquifer characteristics and an understanding of local and regional hydrogeology. Groundwater models are used to estimate direction and rate of transport, dilution, and dispersion of contaminants along the pathway. Commonly used computer models for flow and pathway analysis include PLASM [Prickett and Lonnquist, 1971], the U.S. Geological Survey two dimension model [Trescott and others, 1976] and a three dimensional finite difference model [McDonald and Harbaugh, 1984]. Alternatively, simple analytical flow equations based on Darcy's Law are used for the pathway analysis. Groundwater models predict the location and rate of discharge to streams which allows evaluation of impacts to stream water quality. Impacts to surface water are calculated using seasonal streamflow data and a simple mixing equation based on volume and concentration of contaminants in groundwater.

Prediction of the fate of contaminants in groundwater is important and difficult and requires knowledge of contaminant geochemical behaviour in aquifer materials. For acid waters, transport of many metals is determined by the capacity of aquifer materials to neutralize acidity. Geochemical computer models such as PHREEQE [Parkhurst et al., 1980] may be used to predict thermodynamic stability of solid phases and solubility of elements for various pH and oxidation-reduction conditions. Geochemical models also can predict chemical reactions between groundwater and aquifer materials. Many metals can remain in solution at concentrations that exceed water quality criteria once they are solubilized and mobilized in the environment. For example, elements such as arsenic, molybdenum, selenium, and silver which do not form insoluble oxides may remain in solution even under moderately alkaline conditions. Primary controls and attenuation mechanisms for selected parameters are:

Parameter	Attenuation Mechanisms
Arsenic	Adsorption by iron and manganese oxides; coprecipitation with iron.
Cadmium	Adsorption by clays; $CdCO_3$ precipitation.
Copper	Adsorption by organic matter and hydrous iron and manganese oxides.
Cyanide	Biodegradation, volatization, oxidation, and photolysis.
Lead	Adsorption to clays, organic matter, and iron and manganese oxides.

Parameter	Attenuation Mechanisms
Mercury	Adsorption on clay, silicates and oxide materials.
Nitrate	Vegetative uptake, bacterial denitrification and volatization.
Selenium	Adsorption on, or precipitation with hydrous iron oxides.
Zinc	Adsorption by clays, hydrous iron and manganese oxides, and organic matter.

Mobility of many metals is controlled by adsorption on aquifer materials and in many cases adsorption may control mobility even when solid phases appear to be thermodynamically stable. Predictive methods to determine adsorption affinities and rates for metals and aquifer materials are not well developed and site specific laboratory testing of mine waters and aquifer materials is generally necessary. Laboratory testing usually consists of column testing where mine waters are passed through a column of natural aquifer materials and attenuation of parameters is measured by difference between influent and effluent concentrations. This method is advantageous in that natural geological materials are tested and are allowed to control pH, ionic strength, and thus adsorption behaviour of dissolved constituents. The adsorption capacity of geological materials also can be determined using laboratory bottle roll tests in which the concentration of parameters is varied and results are used to develop Langmuir or Freundlich adsorption isotherms. Accurate prediction of environmental pH conditions and control of pH in laboratory tests is necessary for adsorption isotherms to be valid representations of the natural adsorptive capacity.

Typical results of soil column attenuation results for a gold mine in South Dakota are shown in Table 5. The water used in the column was leachate from leached ore (spent ore) and the soil was from beneath the spent ore disposal area. A 55 cm long plastic column was used in the test. Many column tests at a variety of gold mines have shown excellent attenuation of many parameters by natural soils.

FUTURE PREDICTIVE CONSIDERATIONS

In the future, gold and other metals will continue to be developed at a more rapid pace to satisfy increasing demands for these metals. Future mining will occur on larger and lower grade deposits, in areas of more difficult topography and climate and in rocks with more complex mineralogy.

This will place more emphasis on development of accurate, quantitative predictions of acid water and metals and the impact on environmental resources. In the northwestern United States, future emphasis will continue to be on acid water and metals in surface water and groundwater.

Table 5. Soil Column Attenuation Results for Metals in Spent Ore Leachate

Parameter	Spent ore Leachate	Soil Column Effluent
pH	9.1	6.8
Sulfate	39	46
Cyanide-WAD	0.17	0.007
Arsenic (As)	0.22	<0.005
Barium (Ba)	<0.2	<0.2
Cadmium (Cd)	0.002	0.002
Chromium (Cr)	<0.02	<0.02
Copper (Cu)	0.02	<0.01
Iron (Fe)	0.24	0.03
Lead (Pb)	<0.01	<0.01
Manganese (Mn)	<0.02	0.03
Mercury (Hg)	<0.001	<0.001
Nickel (Ni)	<0.03	<0.03
Selenium (Se)	<0.005	<0.005
Silver (Ag)	<0.005	<0.005
Zinc (Zn)	<0.01	<0.01

The general predictive methodology is relatively simple and can be summarized as follows:

1) Testing of waste rock and tailings to predict generation of acid water and dissolution of metals.

2) Prediction of the quantity of water leaving mining facilities (tailings ponds, mined areas, waste rock dumps and leach ore heaps) and the movement of this water into groundwater and surface water.

3) For metals entering groundwater, the attenuation along the groundwater flow path must be predicted.

4) Calculation of the concentration of metals in groundwater and surface water at compliance points.

5) Determination of compliance with water quality standards both during mining and after reclamation.

Although the overall methodology for predicting acidic water and impacts of these waters is understood, standardized techniques for accurate quantitative predictions are not readily available. To increase the accuracy of predictions, better techniques are needed to:

1) Estimate the rate of acid production including estimates of the concentration of metals and other parameters.

2) Calculate the rate of movement of water through earth covers placed on tailings, waste rock, leached ore heaps and mined areas.

3) Determine the effectiveness of earth materials and aquifers in modifying water quality during movement through these materials.

4) Determine chronic and acute impacts on aquatic organisms in streams receiving contaminated waters.

Future predictive techniques should emphasize computer-based models that allow assessment of a number of designs to allow selection of the most cost-effective options. Prediction of acid drainage is an important step in evaluation of mining and mineral processing projects. The overall focus of predictions for gold mining in the northwestern United States must be on operational and long-term impacts of mine-related water on surface water and groundwater resources.

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