Predicting Water Quality for a High Altitude Mine Waste Facility in Peru

C. James Warren[1], Dawn Kaback[2] Gokhan Inci[2] and Daniel Neff[3]
1. AMEC Foster Wheeler Environment & Infrastructure, Canada
2. AMEC Foster Wheeler Environment & Infrastructure, USA
3. M3 Engineering and Technology Corporation, USA

ABSTRACT

AMEC Environment & Infrastructure (AMEC) was retained by M3 Engineering and Technology Corporation (M3) to provide an assessment of the acid rock drainage and metals leaching potential (ARD/ML) of waste rock and ore to be produced at an open pit copper mine located at high elevation (3,000 – 4,500 masl) in Peru. The mine is expected to produce about 573 Mt of ore for milling, 173 Mt of low-grade ore for heap leach, and about 1,360 Mt of waste rock over 25 years of operation. The current plan is to construct an on-site waste storage facility (WSF) by co-blending milled tailings with waste rock in an alpine valley. The WSF, which will also partially cover the heap leach residue pad located at the top of the valley, will contain underdrains directed to a single pond at the toe. Geochemical testing included analyses of 1000 samples from five major lithologies representing waste rock and ore for acid base accounting and content of total metals. Selected samples of waste rock, simulated tailings, and heap leach residue were submitted for mineralogical, humidity cell, and other geochemical testing. Geochemical results were modeled by considering the configuration of the WSF to predict water quality of the leachate at the toe. Leachate pH is expected to be mildly alkaline due to alkalinity generated primarily by the tailings. Although the heap leach residue is expected to contribute some acidity, alkalinity from the tailings will minimize the contribution. The results indicate that arsenic, chromium, mercury, and zinc may be of possible concern, requiring treatment prior to discharge.

Keywords: Tailings, Alpine, Waste Rock, Humidity Cells, ABA

INTRODUCTION

AMEC Environment & Infrastructure, a division of AMEC Americas Limited (AMEC), was retained by M3 Engineering and Technology Corporation to assess the acid rock drainage and metals leaching potential (ARD/ML) of waste rock and ore to be placed in a high elevation (3,000 – 4,500 masl) waste storage facility (WSF) in Peru. The WSF is designed to contain milled tailings from high-grade ore (573 Mt) co-blended with waste rock (1,360 Mt). The co-blended material is expected to partially cover a spent heap leach residue pad (total 173 Mt) when mining operations cease after 21 years. The WSF including the heap leach residue pad (total 2,106 Mt) will be located in an existing alpine valley with constructed underdrains directing leachate to a pond at the toe.

A geochemical testing program was conducted to enable prediction of potential water quality from the WSF to support mine planning activities. The objective of the program was to develop an integrated geochemical-hydrological loading model to predict water quality at the toe of the WSF using data derived from static and humidity cell testing of waste rock, simulated mill tailings, and heap leach residue as well as local meteorological data.

METHODOLOGY

Sample Selection

A total of 1000 samples were selected for static geochemical testing from available drill core from 205 diamond drill holes totaling 92,760 m spaced about 50 to 75 m apart. Preliminary estimates based on the block model for the mine identified six major rock types (lithologies) as listed in Table 1 with estimated proportions and number of samples selected for testing.

Table 1 Estimated Proportions of Major Identified Lithologies (Rock Types) and Sample Numbers

Lithology	Percentage of Waste Rock	WSF Weighted Proportion	Number of Waste Rock Samples	Number of High-grade Ore Samples	Number of Low-grade Ore Samples
Siltstone	18.2%	12.9%	178	13	4
Quartzite	32.1%	22.7%	494	49	24
Quartz Monzonite (fine-grained)	15.2%	10.7%	16	25	2
Quartz Monzonite (coarse-grained)	19.3%	13.6%	36	20	6
Feldspar-Megacrystic Quartz Monzonite (coarse-grained)	15.3%	10.8%	71	41	13
Monzodiorite	0.4%	Included	5	2	1
TOTAL	100.0%	100.0%	800	150	50

ABA Testing and Assay Database

The 1000 core samples were collected for acid base accounting (ABA) analyses to provide preliminary estimates for the potential acid generating (PAG), or non-PAG nature of the rock. Samples were analyzed for total sulfur, sulfate-sulfur, and pyritic-sulfur (sulfide-sulfur). Organic-sulfur was reported as the difference between total sulfur and the combination of the sulfate-sulfur and pyritic sulfur. The Acid Generating Potential (AGP) was calculated based on sulfide analyses, whereas the. Acid Neutralization Potential (ANP) was determined following the State of Nevada Modified Sobek Procedure (2010). The potential for acid generation was assessed based on Neutralization Potential Ratio (NPR = ANP/AGP).

A metallurgical assay database for the 92,760 m of drill core, containing analyses for a total of 30,858 drill core samples, including concentrations of copper (Cu), molybdenum (Mo), iron (Fe), bismuth (Bi), antimony (Sb), arsenic (As), mercury (Hg), lead (Pb), and zinc (Zn), was reviewed to assess metal leaching (ML) potential prior to kinetic humidity cell testing.

In addition, composite samples representing simulated tailings and heap leach residue obtained from bench/pilot-scale metallurgical testing were submitted for the same ABA analyses used for waste rock and ore samples. The simulated tailings sample was derived from a blend of high-grade ore core samples and the simulated heap leach sample was derived from blended low-grade ore.

Humidity Cell Testing

Based upon results of static testing, kinetic testing (humidity cells) was initiated for nine of the waste rock samples and for single samples of simulated tailings and simulated heap leach residue obtained from bench/pilot-scale metallurgical tests. The nine samples of waste rock were selected to represent each major rock type (lithology), with two samples per lithology; one of either PAG rock (NPR<1) or uncertain (1<NPR<2) categories along with a non-PAG (NPR>2) sample from the same lithology. In addition, consideration was given to samples enriched in total contents of metals [copper (Cu), silver (Ag), molybdenum (Mo), bismuth (Bi), antimony (Sb), and arsenic (As)] based on assay analyses.

Humidity cell testing was conducted based on ASTM D5744-07 and EPA Method 1627. Testing for three of the nine waste rock samples was terminated after 20 weeks, because release rates of key parameters had stabilized. Humidity cell testing for the remaining six waste rock samples was continued for a total of 32 weeks. Humidity cell testing for the simulated tailings and heap leach samples was terminated after 20 weeks. Leachate samples were collected weekly for analysis of:

- pH, specific conductivity, total dissolved solids (TDS), alkalinity, and acidity;
- Concentrations of sulfate, chloride, fluoride, bicarbonate, and nitrate+nitrite nitrogen;
- Concentrations of calcium, magnesium, potassium, and sodium by inductively coupled plasma optical emission spectroscopy (ICP-OES); and,
- Concentrations of dissolved aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, copper, iron lead, manganese, mercury, nickel, phosphorous, selenium, silver, thallium, and zinc by inductively coupled plasma mass spectroscopy (ICP-MS).

Carbonate Analyses

The 11 humidity cell samples (nine waste rock, one simulated tailings and one simulated heap leach residue) were analyzed using a LECO C/S analyzer for (1) total carbon content and (2) carbon content of a subsample digested with hydrochloric acid to predict acid-insoluble carbon. The content of carbonate carbon (acid soluble carbon) was determined by difference and used to calculate carbonate NP. Although only a very limited number of samples were analyzed, the values were extrapolated to the remainder of the 800 sample waste rock database using linear regression to estimate carbonate NP for the entire waste rock database.

Other Analyses

The nine humidity cell waste rock samples were also submitted for X-ray diffraction using Rietveld refinement (RXRD) to provide a semi-quantitative estimate of mineral content. These waste rock samples and the two samples of metallurgical residues representing simulated tailings and heap leach residue were analyzed using the single addition net acid generation (NAG) test. On completion of humidity cell testing, the nine waste rock samples were submitted for particle size (grain size) analysis. Particle size data for composite bench/pilot-scale test samples were determined during metallurgical testing. Grain size analysis is typically used to estimate specific surface area of material in the humidity cells.

RESULTS AND DISCUSSION

Acid Base Accounting (ABA)

Methods for assessment of waste rock and ore as PAG or non-PAG vary depending on jurisdiction. As an initial PAG/non-PAG screening criterion for waste rock, MEND (2009) recommends NPR values greater than 2 to identify non-potentially acid generating (non-PAG) rocks; NPR values between 1 and 2 as having an uncertain acid-generating potential, requiring further testing for accurate assessment; and NPR values less than 1 as rock considered to be potentially acid generating (PAG). All samples with NPR values less than 2 are considered PAG until additional testing has been conducted. These criteria may also be applied to tailings; however, some jurisdictions recognize a lower NPR threshold for differentiating PAG and non-PAG tailings; however this requires site-specific studies. For this study, the MEND screening criteria (MEND, 2009) described earlier were applied to the ore/tailings as well as to the waste rock. It should be noted that the individual ore samples submitted for static testing were not subjected to metallurgical processing prior to analyses. The ABA characteristics and metal content of tailings derived from the ore could differ greatly from these analyses depending on the milling and heap leach processes. Average values for NPR, calculated from the ABA data (ANP/AGP) for the various lithologies where AGP is based on pyritic sulfur are summarized in Table 2.

Table 2 Proportion of 1000 Sample Database Based on NPR and Carbonate NPR (CNPR)

Lithology	Number of Samples	Sobek-NP		Avg.	Carbonate NP		Avg.
		NPR<2	NPR>2	NPR[1]	NPR<2	NPR>2	CNPR[1]
Low-grade Ore	50	48%	52%	1.8	72%	28%	0.6
High-grade Ore	150	48%	52%	1.4	79%	21%	0.4
Siltstone	178	14%	86%	2.8	22%	78%	1.1
Quartzite	494	20%	80%	1.6	56%	44%	0.2
Quartz Monzonite (fine-grained)	16	6%	94%	6.6	38%	63%	1.1
Quartz Monzonite (coarse-grained)	36	6%	94%	6.2	6%	94%	4.3
Feldspar-Megacrystic Quartz Monzonite	71	11%	89%	5.1	42%	58%	1.4
Monzodiorite	5	40%	60%	0.9	nd	nd	nd

Note: 1. Average for samples within a lithology or grade category
nd = not determined

Individually, the Siltstone, Quartz Monzonite (fine-grained), Quartz Monzonite (coarse-grained) and Feldspar Megacrystic Quartz Monzonite (coarse-grained) lithologies are non-PAG; collectively representing 67% of the waste rock. The Monzodiorite (<1% of the waste rock) was classified as PAG with an average NPR of 0.9, and the Quartzite (32% of the waste rock) was classified as uncertain with respect to ARD potential with an average NPR of 1.7. High-grade ore (feed stock for the mill) and low-grade ore (for use in the heap leach facility) had average NPR values of 1.4 and 1.8, respectively, indicating that the samples have uncertain ARD potential (1<NPR<2) with respect to the initial screening criteria. Overall, 52% of the ore samples were classified as non-PAG (NPR>2); 33% PAG (NPR<1) and 15% uncertain (1<NPR<2). Average values for Carbonate Neutralization Potential (CNPR) in Table 2 are discussed in the sections below.

Carbonate Carbon and NAG pH

The content of carbonate carbon for the nine waste rock humidity cell samples was used to calculate carbonate neutralization potential (CNP as $CaCO_3$ equivalent) for all samples in the database via linear regression. To calculate CNP, it is assumed that all neutralization potential (NP) is due to carbonate. For the waste rock and ore samples, CNP values represented between 15% and 70% of the Modified Sobek NP with an average of 26%. The values for carbonate content and the resulting carbonate NPR values (CNPR) show high variability with respect to acid generation potential and that the Quartz Monzonite (coarse-grained), Quartzite, and Feldspar-Megacrystalic Quartz Monzonite (coarse-grained) are either PAG (CNPR<1) or uncertain (1<CNPR<2) with respect to acid generation potential. Although the variability within each lithology (represented by only 2 samples each) was high, the CNPR values agreed with the NAG pH results. Comparison of NPR and CNPR values, NAG pH, and corresponding ARD classifications for the nine individual humidity cell samples is summarized in Table 3. Tailings and heap leach residue CNPR values and classification are compared to NAG pH classification in the same table. These values were used to calculate the average CNPR values for each lithology listed in Table 2.

Refinement of ABA Classification

Although the degree of variability for the CNP is higher than the Modified Sobek NP due to the limited number of samples, the amount of NP supplied by carbonate alone (CNP) provides a more conservative estimate of effective NP in the long term compared to modified Sobek NP values. Neutralization potential (NP) based on carbonate content (CNP) was used instead of Sobek NP as the primary means to assess ARD potential in these materials. Values for average CNPR, calculated as CNP/AGP, where AGP is based on pyritic sulfur, for the individual humidity cell samples with different lithologies is provided in Table 2 along with the average Sobek NPR values. Based upon the Sobek NP and the sulfide AP measurements, the waste rock had a weighted average NPR (based upon estimated percentages of the various lithologies in the waste facility; Table 1) of 3.9, indicating that overall the WSF is non-PAG. Based on the carbonate-carbon data, the weighted average of CNPR calculated for the waste rock overall based on the proportions of each lithology (Table 1) was 1.7, indicating that the waste rock, overall, has uncertain ARD potential. Based upon the CNPR data (Table 2), the quartzite waste rock was PAG with an average value of 0.2. The Siltstone, Quartz Monzonite (fine-grained), and Feldspar-Megacrystic Quartz Monzonite (coarse-grained) had CNPR values between 1 and 2, indicating uncertain ARD potential and the Quartz

Monzonite (coarse-grained) had an average CNPR of 4.3, indicating non-PAG material. Both the high-grade and low-grade ore had CNPR values less than 1, indicating that these materials are PAG. Note that these estimates for ARD potential for the site should be viewed as having a very high degree of variability, as the data were extrapolated to all 1000 samples using the original static data based on the carbonate analyses for the nine waste rock humidity cell samples, one tailings (cf. high-grade ore) sample, and one heap leach (cf. low- grade ore) sample.

The NAG test uses pH of 4.5 as a cutoff to differentiate between PAG and non-PAG rock. Based on this assessment, five of the nine waste rock samples were predicted to be PAG, including both samples of quartzite, and four samples were predicted to be non-PAG (Table 3). The simulated tailings sample had a NAG pH of 9.2, indicating it was non-PAG and the master composite sample (heap leach residue/low-grade ore) had a NAG pH of 3.4, indicating that it was PAG (Table 3).

Table 3 ABA and NAG pH Results for Individual Samples from Humidity Cells

Sample ID/Lithology	NPR ANP/AGP	ARD Class	CNPR CNP/AGP	ARD Class	NAG pH	ARD Class
015/Siltstone	10	Non-PAG	8.1	Non-PAG	6.0	Non-PAG
198/Siltstone	1.3	Uncertain	0.0	PAG	3.3	PAG
050/Quartzite	5.7	Non-PAG	0.9	PAG	3.5	PAG
101/Quartzite	1.4	Uncertain	0.2	PAG	3.1	PAG
247/Quartz Monzonite (fine-grained)	0.4	PAG	0.0	PAG	4.1	PAG
247b/Quartz Monzonite (fine-grained)	17	Non-PAG	5.4	Non-PAG	5.4	Non-PAG
017/Quartz Monzonite (coarse-grained)	1.4	Uncertain	1.0	Uncertain	5.2	Non-PAG
142/Feldspar-Megacrystic Quartz Monzonite	8.0	Non-PAG	1.5	Uncertain	9.9	Non-PAG
164/Feldspar-Megacrystic Quartz Monzonite	0.6	PAG	0.2	PAG	3.3	PAG
MT / Simulated Mill Tailings	nd	nd	1.6	Uncertain	9.2	Non-PAG
MC / Simulated Heap Leach Residue	nd	nd	0.9	PAG	3.4	PAG

Mineralogical Analyses

Results for mineralogical content of the nine samples, as determined by RXRD are as follows:

- The quartzite lithology was predominantly quartz (>95%) with some muscovite and metallic iron with one sample contained measurable quantities (0.5%) of pyrite.
- The siltstone samples contained quartz and muscovite (about 87%) with minor kaolinite and rutile. One sample also contained K-feldspar, andalusite, and detectable pyrite (0.4%).
- The quartz monzonite samples (fine-grained and coarse-grained) had similar mineralogy, containing quartz, feldspars, muscovite and kaolinite. The coarse-grained sample and one of

the fine-grained samples contained 2-3% jarosite, suggesting that the materials may have an acid generating source mineral in addition to sulfides (e.g., pyrite).

- The two Feldspar-Megacrystic Quartz Monzonite samples were very similar mineralogically, containing quartz, feldspars, muscovite, chlorite, pyrite, calcite, and siderite. Siderite ($FeCO_3$) is slow reacting compared to calcite, and estimates for carbonate NP were corrected in these two samples based on the mineralogical analyses.

Waste Rock Humidity Cells

After 20 weeks of waste rock humidity cell testing, leachate concentrations in three of the nine samples was terminated because release rates of key parameters had stabilized. The remaining six waste rock humidity cell samples were continued through 32 weeks. Based on humidity cell testing, preliminary estimates for exhaustion of sulfide-S (primary acid generation source) and carbonate NP (neutralization source) for waste rock samples in the nine humidity cells are summarized in Table 4. It should be noted that estimates for the humidity cells are based on best available data for the humidity cells, which may or may not have stabilized. Estimated rates of sulfate loss from the columns ranged from 0.25 to 26 mg/kg/week. Rates of alkalinity loss were similar for all columns at about 2.5 mg/kg/week with the exception of the Feldspar-Megacrystic Quartz Monzonite samples, which were 8.7 and 6.9 mg/kg/week. Using these values, predicted times required to exhaust sulfide and alkalinity in the humidity cells did not agree well with the original Sobek NPR values calculated from the static ABA testing. This indicates a high amount of variability within each lithology, particularly those samples containing low concentrations of sulfide and carbonate alkalinity. Note that these time estimates are for crushed samples under ideal laboratory conditions, whereas rates in the field are typically slower due to lower specific surface area values associated with larger rock fragments, ambient soil temperatures, and less contact with reactive surfaces as water flows among the larger rock fragments.

Table 4 Estimates of Years for Exhaustion of Sulfide and Carbonate in the Humidity Cells

Sample ID/ Lithology	CNPR CNP/AGP	Years to Exhaust Sulfide	Years to Exhaust Carbonate	Year to Acidification
015/Siltstone	8.1	23	19	19
198/Siltstone	0.0	14	0	Immediate
050/Quartzite	0.9	<1	38	Never
101/Quartzite	0.2	53	6	6
247/Quartz Monzonite (fine-grained)	0.0	4	6	Never
247b/Quartz Monzonite (fine-grained)	5.4	26	26	Never
017/Quartz Monzonite (coarse-grained)	1.0	157	5	5
142/Feldspar-Megacrystic Quartz Monzonite	1.5	<1	0	Never
164/Feldspar-Megacrystic Quartz Monzonite	0.2	11	13	Never

Tailings and Heap Leach Residue Humidity Cells

Humidity cell testing and analyses for the two metallurgical residue samples were completed through 20 weeks. Results indicated that the pH of the leachate from the Master Composite heap leach residue sample was 5.3 and the filtered tailings was 7.8. These data are assumed to represent long-term water quality for these materials, although they may or may not have stabilized during the 20-week testing. Based on the humidity cell leachate results, concentrations of metals released from the tailings are not anticipated to contribute high amounts of metals to the WSF leachate; however, it should be noted that the humidity cell data do not represent stabilized conditions; it is likely that metal leaching may not have been initiated due to the limited timeframe for leaching.

PROPOSED WASTE STORAGE FACILITY

Based on the mine plan, mill tailings derived from high-grade ore (about 573 Mt) are to be mixed with waste rock (about 1,360 Mt) for permanent storage in the on-site WSF. The WSF will also partially cover the heap leach facility (HLF; about 173 Mt), which will have been treated (surface irrigation) with about 2% H_2SO_4 for metal extraction. After mining operations cease (after 21 years) the entire WSF including the HLF not covered by co-mingled waste rock and tailings will be capped with a 2.5 m thick layer of tailings compacted to a dry bulk density of about 1.6 tonnes/m^3 and the compacted tailings will be covered with a 1 m thick layer of “inert” waste rock composed of roughly equal portions of Quartz Monzonite fine-grained; Quartz Monzonite coarse-grained and Feldspar-Megacrystic Quartz Monzonite coarse-grained lithologies. The waste rock layer will be covered with 0.5 m of growth media (soil) to support re-vegetation.

Water quality predictions for the leachate and ARD potential of the blended storage facility was based on the following assumptions:

- Release rates of acidity/alkalinity and metals from the co-mingled WSF at constant rates based on steady state data obtained from the humidity cells and on the proportion of materials during construction and after completion of mining;
- Instantaneous placement of the 2.5 m thick compacted tailings cover and 1 m of waste rock after 21 years of mining reducing the volume of infiltrating water. The volume and quality of water released at toe decrease and the results of the model presented herein represent worst case conditions;
- Ideal (perfect) mixing of rock types within the waste rock dump according to proportion of their lithologies (Table 1);
- Mill tailings are allocated to fill all pore space within the waste rock;
- The final configuration of the WSF covers an area of about 6,702,780 m^2 (6.7 km^2) receiving average annual precipitation of 963.8 mm, of which about 95% is received during the months of October to April. Evaporation from the surface of the WSF is assumed to be about 50% of precipitation. Losses from surface runoff and to groundwater are negligible.
- The HLF is assumed to be 100% PAG as it is leached with 2% H_2SO_4
- The proportion of PAG and non-PAG materials in the WSF are based on carbonate NP and a cut-off CNPR value of 2;
- Rates of releases for metals are based on the humidity cell data scaled up to field conditions.
- The waste rock is assumed to have an effective specific surface area of 13 m^2/tonne based on a total surface area of 20 m^2/tonne and 65% contact with water;

- Tailings and the heap leach residue are assumed to have specific surface areas the same as the respective humidity cell materials and will react to provide similar water quality.
- For the purposes of calculations, the internal temperature of the WSF is assumed to be constant at 15°C.

WATER QUALITY PREDICTIONS

Based on available data and assumptions, estimates for water quality of the WSF leachate are provided in Table 5. Leachate from waste rock will likely have a pH of approximately 4.6, calculated as weighted proportions of leachate contacting waste rock, tailings, and heap leach residue, at equal rates of flow through all materials, with equal contact. In reality, the majority of water flowing through the WSF is likely to be in contact with the larger pores of the waste rock with lesser contributions from the tailings and heap leach residue; however, estimates for water flow and proportions contacting each of the materials require a more detailed hydrological and hydrogeological assessment.

Table 5 Estimated Water Quality for WSF Leachate

Parameter	Units	Leachate	MPL[1] Liquid Effluent	NEQSW[2] Category 1
pH	su	4.6	6-9	6.5-8.5
Sulfate	mg/L	469		250
Calcium	mg/L	54		
Magnesium	mg/L	8		
Potassium	mg/L	21		
Sodium	mg/L	15		
Aluminum	mg/L	4.0		0.2
Antimony	mg/L	0.030		0.006
Arsenic	mg/L	0.242	0.1	0.01
Barium	mg/L	1.383		0.7
Beryllium	mg/L	0.006		0.004
Cadmium	mg/L	0.006		0.003
Chromium	mg/L	0.093	0.1	0.05
Copper	mg/L	12	0.5	2
Iron	mg/L	53	2	0.3
Lead	mg/L	0.045	0.20	0.01
Manganese	mg/L	0.400		0.1
Mercury	mg/L	0.001	0.002	0.001
Nickel	mg/L	0.116		0.02
Phosphorus	mg/L	0.278		0.1
Selenium	mg/L	0.050		0.01
Silver	mg/L	0.014		
Thallium	mg/L	0.003		
Zinc	mg/L	0.119	1.5	3

Notes: 1.Maximum Permissible Limits to unload liquid Effluents by Metallurgical Mining Activities.
2. National Environmental Quality Standards for Water Category 1: Potable Water

It is anticipated that water will flow through the much finer textured mill tailings at a much slower rate and consequently the volume of flow contributed from the tailings is expected to be less compared to flow and loadings from the waste rock; however, an estimate of the magnitude and proportions are beyond the current scope of this work.

The key parameters of concern appear to be pH, arsenic, copper, and iron. Some of the iron released from the WSF may precipitate from the leachate as it becomes more oxygenated by contact with the atmosphere. This may also reduce the concentrations of copper and arsenic due to co-precipitation or adsorption; however, concentrations may or may not be reduced to levels acceptable to Peruvian regulations, and thus may require active water treatment.

CONCLUSIONS

Based on static and humidity cell testing and the water quality model described herein, predictions indicate that leachate from the WSF is anticipated to contain elevated concentrations of iron, arsenic, and copper as well as acidic pH values less than the acceptable minimum required by Peruvian authorities for discharge to the environment. Water treatment measures may be required to reduce concentrations of metals as well as increase pH prior to discharge to the environment. Additional information on flow conditions, a detailed hydrological and hydrogeological assessment and water quality of downstream waters are required for further assessment.

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