AN EMPIRICAL TECHNIQUE FOR PREDICTING THE CHEMISTRY OF WATER SEEPING FROM MINE-ROCK PILES[1]

Kevin A. Morin[2] and Nora M. Hutt[3]

Abstract: Mine-rock piles are complex hydrogeologic systems. As a result, the current knowledge of their physical and chemical hydrogeology is too limited to permit accurate predictions of water chemistry through time based on detailed simulations of their internal processes. However, a simplistic empirical model based on general knowledge and available data can be used to obtain rough estimates of seepage chemistry through time. This empirical model is based on five factors: (1) the production rates of metals, nonmetals, acidity, and alkalinity under acid and pH-neutral conditions, (2) the volume rate of flow through the rock pile based on infiltration of precipitation, (3) the elapsed time between infiltration events, (4) the residence time of the water within the rock pile, and (5) the percentage of mine rock in the pile flushed by the flowing water. The last factor is most difficult to define at many minesites, but can be assumed due to its apparently frequent narrow range of 5 to 20%. A hypothetical example illustrates how to use the model and highlights other complications like secondary-mineral precipitation that may also have to be considered. A field example based on data from an actual minesite demonstrates the accuracy of the model as compared to measured concentrations. Again, this model ignores many complexities of mine-rock piles and is thus only useful for rough estimates of future chemistry.

Additional Keywords: acidic drainage, mine-rock piles, waste rock, geochemical predictions, hydrogeology

Background and Objectives

A mining operation can consist of several primary and secondary components such as an open pit or underground workings, tailings, waste-rock dumps and ore stockpiles, and various dams, roads, and construction pads made of mine rock (e.g., Morin 1988). An integrated program for the prediction of future movement of water and its associated chemistry is obviously of great value to any mining operation about to begin, currently operating, or about to close. Predictive geochemical techniques for tailings have received preferential attention over the last 10 yr, as demonstrated in Canada by the numerous reports generated under contracts for the now defunct National Uranium Tailings Program and the current federal Mine Environment Neutral Drainage (MEND) Program (e.g., Senes 1991). Predictive procedures for pits and underground workings have also been developed under MEND and the British Columbia AMD Task Force to an initial level (Morin 1991) and are now being expanded (Morin and Hutt 1994, Morin 1994). However, predictive geochemical techniques for mine-rock dumps, dams, piles, and roads (hereafter simply called "piles") are still tentative due to their complexity.

Mine-rock piles are complex hydrogeologic systems, and current hydrogeologic theory is not able to characterize them accurately (e.g., Morin et al., 1991). As a result, this limited knowledge of the physical and geochemical aspects of piles precludes accurate predictions of future water chemistry through impressive mathematical equations without empirical "fitting" factors. Instead, a simpler model for rough estimates of future

---

chemistry can be based on an empirical approach.

The first objective of this paper is to present the five factors that form an empirical model for the prediction of aqueous chemistry issuing from a mine-rock pile. These factors are (1) the production rates of metals, nonmetals, acidity, and alkalinity under acid and pH-neutral conditions from a unit weight of rock, (2) the volume rate of flow through a rock pile based on infiltration of precipitation, (3) the elapsed time between infiltration events, (4) the residence time of the water within the rock pile, and (5) the percentage of mine rock in the pile flushed by the flowing water. The second objective of this paper is to present a hypothetical example followed by an actual field example. In the field example, the empirical model is calibrated to one mine-rock pile at a minesite and then used in predictive mode for the other piles in various stages of acid generation.

Factor 1: Geochemical Production Rates

The primary reason for concern over some mine-rock piles is that they contain reactive minerals that can release metals and nonmetals, such as copper, sulfate, acidity, and alkalinity. These reaction products can then be swept away by any water flowing over the rock surfaces or can accumulate on unflushed surfaces. The unflushed surfaces do not immediately influence water chemistry, but can affect chemistry during irregular events such as the shifting of the pile or plugging of preferential flow channels (see factor 5) so that previously unflushed surfaces become regularly flushed. In any case, it is the prediction of the regular removal rate of the reaction products that is the purpose of this paper. For simplicity, only the regularly flushed surfaces are considered here.

The most common method for obtaining production rates is often labelled "kinetic tests" (e.g., fig. 1). Such tests involve repetitive monitoring of water passing over a mass of rock for several months to years. Under laboratory conditions, a common kinetic test involves "humidity cells" in which effluent concentrations often asymptotically approach long-term production rates after 30 to 40 weeks of weekly rinsing and analysis. Because sulfide oxidation and metal leaching can often be treated as kinetic (time-dependent) processes, the production rates can be expressed in units of milligrams of metal or non-metal per unit weight (kilograms) or surface area (square meters) of rock per unit time, such as 10 mg zinc/kg of rock/wk.

Figure 1. Example of sulfate production rates from a mine-rock kinetic test.

One area of confusion in published literature lies in distinguishing between unit-surface-area and unit-weight rates, which implicitly includes the issues of (1) whether the rock occurs as coarse boulders or fine rock and (2) whether fine rock or boulders should be used in kinetic testing. For practical purposes, there is often little reason for this confusion or for considering the grain size. Laboratory-based kinetic tests often use rock ground to finer than 1/4 inch. This is generally representative of most of the reactive particle surface area in a pile, as shown numerically in the next paragraph.

With the assumptions that rock particles resemble cubes (other shapes can also be considered) with a length of 0.2 m and that the bulk density of a rock mass is 1.8 metric tonnes (mt) a cubic meter, then 1 mt of rock will have a volume of 0.555 m^3 and contain an average of 69.4 rock particles with a total particle surface area of 16.6 m^3/mt. This would seem relevant to literature reports of coarse rock accumulating at the base of end-dumped piles.
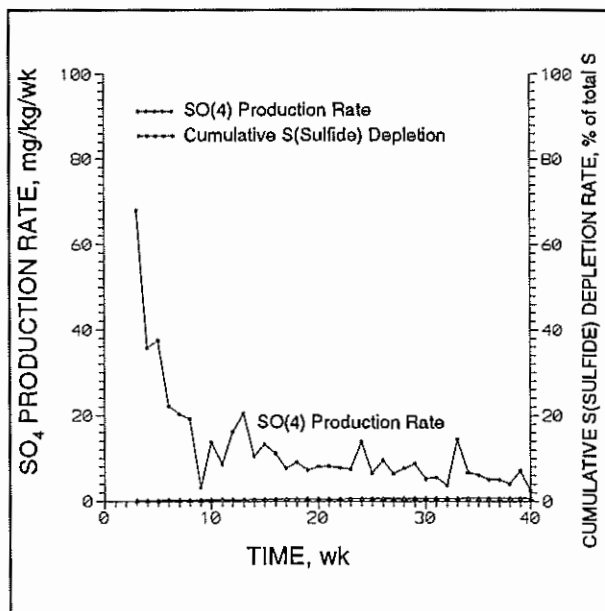
In reality, this preferential accumulation is not particularly important because there is often some finer rock located between the coarse rock. If 1 mt of rock consisted 80% of rock particles with a length of 0.2 m (as above) and 20% with a length of 0.0032m (average of minus 1/4 inch used in laboratory kinetic tests), which would not even completely fill the coarser porespace, then the particle surface area of this 1 mt would be 221 m³, with only 6% coming from the coarse fraction (table 1). Consequently, the assumption that all the rock is coarse can result in errors of more than a factor of 10 on the reactive surface area per unit weight, whereas the assumption that all the rock is fine will often result in errors of less than a factor of 5. In light of the complexities of a pile, the general nature of this empirical model, and the desire for a safety factor in the calculations, the coarse fraction is ignored with no unwarranted effect on the predictions. As a result, the production rates from laboratory-based kinetic tests as mg/kg/wk can often be used for an entire pile directly with no great concern for grain-size effects.

Table 1. Effect of grain size on reactive surface area per unit weight (see assumptions in text).

COARSE FRACTION (0.2 m)		FINE FRACTION (0.0032 m)		TOTAL SURFACE AREA (m²)	% OF TOTAL FROM COARSE FRACTION
% TOTAL WEIGHT	SURFACE AREA(m²)	% TOTAL WEIGHT	SURFACE AREA(m²)		
0	0	100	1040	1040	0
10	1.66	90	936	938	0.18
20	3.32	80	832	835	0.40
30	4.98	70	728	733	0.68
40	6.64	60	624	631	1.05
50	8.30	50	520	528	1.57
60	9.96	40	416	426	2.34
70	11.6	30	312	324	3.58
80	13.3	20	208	221	6.01
90	14.9	10	104	119	12.5
95	15.8	5	52	67.8	23.3
100	16.6	0	0	16.6	100

Factor 2: Infiltration of Water

If rock has significant geochemical production rates (factor 1), but no water moves through the pile, then none of the reaction products will leave the pile. In effect, a lack of infiltration results in containment of the products, but in reality there will be infiltration events even in arid climates. Both the volume of infiltrating water (this factor) and the elapsed time between infiltration events (factor 3) affect the concentrations and loadings seen in the basal seepage. For example, arid climates can sometimes generate high concentrations (as mg/L) because there may be little regular infiltration to dilute the reaction products that accumulate between infiltration events.

Water movement into and through a pile can be initiated by a relatively small precipitation event, which would not lead to infiltration in finer-grained soils (ElBoushi 1975). Thus, even minor rainfall must be considered in the empirical model. However, precipitation events are relatively easy to define based on climatic monitoring regularly conducted at most mines (e.g., fig. 2). As the precipitation falls, some water is lost to evaporation and to runoff if the top of the pile is relatively fine-grained. A general rule of thumb may be that perhaps 40 to 60% of precipitation will infiltrate into the rock, but the actual value at a site should be determined from local monitoring and modelling. In any case, daily precipitation (e.g., fig. 2) is mathematically converted into infiltration based on the minimum amount to initiate infiltration and the infiltration factor.
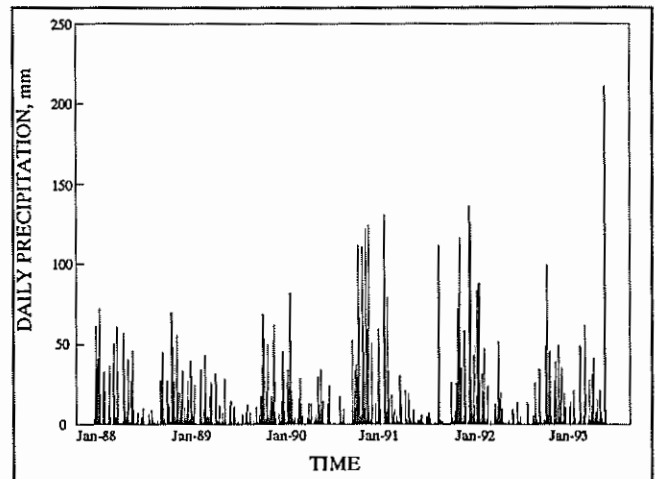

Figure 2. Example of daily-precipitation records at a mine.

Factor 3: Elapsed Time Between Infiltration Events

The importance of this factor comes from the realization that infiltration does not occur every day and that, on days when there is no precipitation, reaction products (factor 1) are accumulating in the flow channels (factor 5). As a result, when infiltration finally appears after a delay, concentrations are notably higher than during regular daily rainfall. This behavior has been noted in various mine-rock dumps and in small-scale in-field rock piles (e.g., Rescan 1992, Norecol, Dames, and Moore 1993).

The elapsed time between infiltration events is easily obtained from climatic data at a minesite (e.g., fig. 1) with the realization that there is a minor threshold below which no infiltration will occur (ElBoushi, 1975). However, due to movement of gas and humidity within piles and the anticipated effects of condensation during daily and seasonal cycles, there may be some flushing of rock surfaces in the absence of infiltration (Morin et al. 1991). Although there is no field evidence for cyclic condensation in piles, its importance has been documented in underground mines (Morth et al. 1972). Additionally, the field example later in this paper shows that average annual precipitation, distributed on a daily basis and assuming flushing of rock surfaces occurred daily, was sufficient to obtain reasonable results. Consequently, the actual importance of infiltration events relative to other processes capable of generating water movement within a pile remains unclear.

Factor 4: Residence Time of Water Within a Pile

This factor is actually a refinement to the previous one. The previous factor addressed the elapsed time between infiltration events, but this factor considers the field studies which show that infiltrating water can require hours to days to pass through a pile and can actually be delayed for greater lengths of time at locations where perched water tables exist (Morin et al. 1991 and 1994). For example, if two infiltration events occur within 48 h in the upper portion of a pile, but the water from both events is caught in a perched groundwater zone at intermediate depths, then the underlying rock surfaces continue to generate reaction products until the water passes through the perched zone. For example, the water from various infiltration events may pass through the upper half of a pile 7 days apart (factor 3), but may pass through the lower half at almost the same time as one event.

This is an interesting factor in that it touches on some complexities in mine-rock hydrogeologic systems, but the delineation of the irregularities is beyond the current ability to accurately detect and monitor them. So, while this factor may become more important in the future, this current empirical model assumes that the elapsed time

between seepage events at the base is equal to the elapsed time between infiltration events. Toe-ditch monitoring as discussed under factor 5 can sometimes be used to evaluate the validity of this assumption.

Factor 5: Percentage of Rock Surfaces Flushed by Water Flow

This factor more than the previous four reflects the true complexity of a mine-rock pile by recognizing that preferential channels for water flow develop in a mine-rock pile (fig.3; see also ElBoushi 1975 and Morin et al. 1991) and that for piles with heights greater than a few meters only 5 to 20% of rock surfaces may be regularly flushed by infiltration events (factor 3). There is currently no direct method for measuring the amount of flushed surfaces, but it can be calculated from a combination of the previous factors and on-site monitoring data of toe-drainage ditches or groundwater monitor wells. The calculation of this factor from the other information highlights both the empirical model's weakness, in that all factors cannot be measured, and its value and simplicity in that (1) a complex factor beyond current capability to measure can be empirically determined as explained below, (2) this complex factor is often in the range of 5 to 20% in full-size rock piles so that its measurement is not required for rough estimates, and (3), once the factor is calculated, the model can be used in a predictive mode as shown in the field example below.
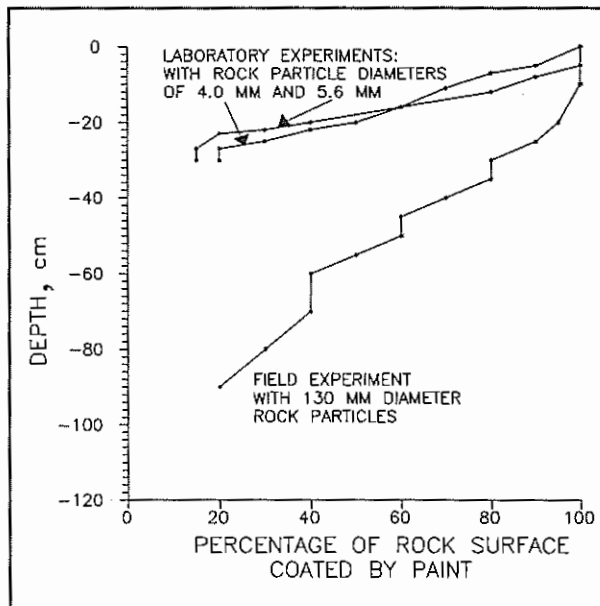

Figure 3. Development of preferential flow channels in rock piles (from ElBoushi, 1975).

Where toe ditches are monitored for flow and chemistry, the average residence time of water in the pile (factor 4) will become apparent when the time of precipitation is compared with the time of maximum flow in the ditch. Additionally, the flow multiplied by concentration will provide a loading, which will in turn reveal the amount of rock flushed to obtain the loading, when the loading is divided by the production rates (factor 1). When this amount of rock is divided by the total weight of rock in the pile, the percentage of flushed rock surface (factor 5) is obtained. In effect, factor 5 is back-calculated from factors 1 through 4 and the predictive targets of the model: the seepage flows and chemistry. This calculation of factor 5 represents calibration of the model to current conditions and no doubt includes effects of other factors not explicitly considered in the model. In any case, the few case studies for which factor 5 has been back-calculated and the direct measurements by ElBoushi (1975) indicated the percentage of rock regularly flushed often lies in the range of 5 to 20%.

It is worthwhile to briefly consider here the remaining 80 to 95% of rock surfaces that can accumulate reaction products year after year. Some of these surfaces would be flushed when extreme infiltration events occur. The regular flow channels would thus be overwhelmed, and the excess water would spill over onto adjacent rock surfaces (see the field example below). Other surfaces may not be flushed until other events occur, such as the shifting of the pile to form new flow channels or the plugging of old flow channels by fine rock or mineral precipitants. These events should be considered in long-term predictions, but are not considered here for simplicity and brevity.

Hypothetical Example

With all of the five empirical factors defined above, a hypothetical example is timely to demonstrate the operation of the model. The hypothetical pile is 600 m long, 300 m wide, and 20 m high. It contains 6.5 million

mt of rock. The long-term production rate (factor 1) of zinc was measured in a humidity cell at 5 mg/kg/wk. Precipitation events generate 1 mm of infiltration (factor 2) and occur every 2 days (factor 3). The elapsed time between flushing events throughout the pile is set equal to the infiltration events of every 2 days (factor 4). The percentage of total rock surface flushed is assumed to be 10%. As a result, the concentration of zinc predicted in the toe seepage is 506 mg/L (table 2). Such a high concentration is possible in acidic waters, but is unexpected in pH-neutral waters due to the solubility of secondary zinc minerals such as sulfates and carbonates. Consequently, not all of the zinc may report to toe seepage. If observed zinc concentrations in the toe seepage were 250 mg/L, or if predicted solubility levels based on geochemical models such as MINTEQ (Allison et al. 1990) were 250 mg/L, then approximately 50% of the produced zinc would be retained in the pile as relatively soluble zinc minerals. These minerals would then be capable of dissolving at a later time to maintain or raise concentrations in toe seepage should one or more other parameters such as pH change.

Table 2. Summary of the hypothetical example for mine-rock flushing.

Factor	Hypothetical Value
1	Geochemical production rate of zinc = 5 mg/kg/wk
2	Precipitation event is 1 mm or 180,000 L over the surface of the pile
3	Infiltration event occurs every 2 days so that the rock accumulates 1.4 mg Zn/kg between events [(5 mg kg^{-1} wk^{-1} / 7 d wk^{-1}) * 2 d]
4	Simplified in this example: seepage events occur every 2 days like infiltration
5	10% of the rock or 650 million kg is flushed by the infiltration
RESULT	PREDICTED CONCENTRATION: (1.4 mg Zn/kg) • (650,000,000 kg) / 180,000 L = 506 mg Zn/L

Field Example

This example is based on geochemical work performed at a mine in Canada that has several mine-rock piles. The model was first applied to one of the piles for which some data on flow and chemistry were available, in order to calculate the percentage of rock surfaces flushed and ensure reasonable values were obtained. The model was then used in predictive mode to estimate water chemistry in toe seepages at other piles under acidic and pH-neutral conditions.

At this site, daily climatic data were not available. Instead monthly averages were available for a nearby location and, for the purposes of average annual predictions, average annual precipitation was used and was assumed to infiltrate on a daily basis. Production rates were obtained from a series of humidity cells operated for a minimum of 40 weeks. Back-calculations for one pile (fig. 4) showed that on average approximately 5% of the rock surfaces (based on zinc) were flushed by most infiltration events, but the flow channels were apparently overwhelmed at ditch flows above 400 m^3/d. The lower rock-surface flushing based on copper reflects the loss of aqueous copper within the dump to secondary mineral precipitation, as indicated by visual observations and MINTEQ calculations.
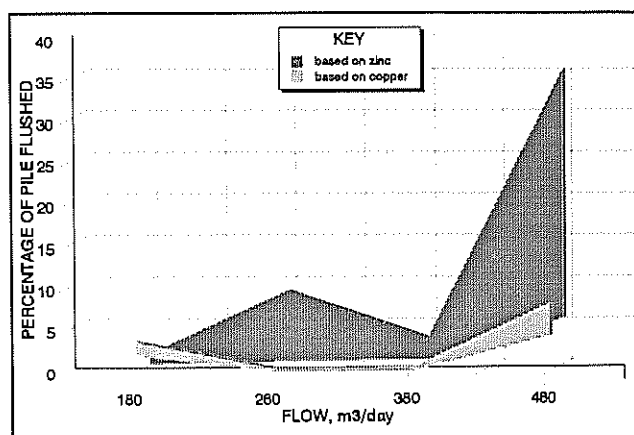

Figure 4. Example of rock-surface flushing as a percentage of total surface area versus toe-ditch flow rate.

17

With a value of 5% used for factor 5, concentrations for other piles were predicted under acidic and pH-neutral conditions. These values were often in general agreement with observed concentrations around the site at pH 2.5 and pH 7.0 (table 3), except for parameters whose concentrations are regulated within the piles by secondary-mineral precipitation and thus should not be found at the predicted concentrations. Based on these results, the empirical model was taken as a general predictor for the minesite with assistance from MINTEQ, and was used to predict changes in concentrations when a particular pile was expected to exhaust all neutralization potential and become acidic.

Table 3. Comparison of predicted and observed values for the field example.

Parameter (mg/L)	ACIDIC (pH 2.5)			pH-NEUTRAL (pH 7.0)		
	Predicted	Average Observed	Highest Observed	Predicted	Average Observed	Highest Observed
Acidity mg/L	4300	3420	8230	~0	22	290
Sulfate mg/L	4100[1]	2000	9230	1700[1]	2000	3300
Cadmium mg/L	0.40[1]	0.07	0.07	0.99[1]	<0.015	<0.015
Copper mg/L	310[1]	600	600	2.0[1]	0.20	5.0
Nickel mg/L	1.6	0.84	2.1	0.01	0.02	0.2
Lead . mg/L	4.4[1]	<0.05	<0.05	10[1]	<0.05	<0.05
Zinc . mg/L	4.0	5.4	28	1.1	0.056	20
[1] These parameters should not appear at predicted levels because secondary-mineral precipitation is limiting their concentrations according to MINTEQ evaluations.						

The relatively good agreement of predicted and observed values not affected by mineral precipitation in table 3 is notable because of the assumption that average precipitation was distributed evenly on a daily basis in the calculations. In other words, chemistry was well predicted, whereas transient flow rates were not. This may indicate that water-flow-generating processes such as condensation are resulting in near-daily flushing of rock surfaces within flow channels. There is insufficient information at this site to further evaluate and resolve such issues.

Conclusion

This paper has presented an empirical model for general predictions of chemical concentrations in seepage from mine-rock piles. This model is based on five factors that account for, but simplify, geochemical production rates, water movement, and rock-surface flushing. The hypothetical example demonstrated the model, but indicated that other processes like secondary-mineral precipitation may also have to be considered. The field example based on an actual minesite showed that relatively good agreement was found between model predictions and observed concentrations under acidic and neutral pH conditions, except for parameters affected by mineral precipitation.

Acknowledgements

'Ua mau ke ea ō ka 'āina i ka aloha 'āina

References

Allison, J.D., D.S. Brown, and K.J. Novo-Gradac. 1990. MINTEQA2/PRODEFA2, a geochemical model for environmental systems: Version 3.0 User's Manual. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia, USA.

ElBoushi, I.M. 1975. Amount of water needed to initiate flow in rubbly rock particles. Hydrology 27: 275-284.

Morin, K.A. 1994. Prediction of water chemistry in open pits during operation and after closure. In 18th Annual Mine Reclamation Symposium, Technical and Research Committee on Reclamation. (Vernon, British Columbia, April).

Morin, K.A. 1991. Acid drainage from mine walls: The Main Zone Pit at Equity Silver Mines. Report for the British Columbia Acid Mine Drainage Task Force and the Mine Environment Neutral Drainage (MEND) Program.

Morin, K.A. 1988. Groundwater contamination from precious-metal, base-metal, uranium, phosphate, and potash (KCl) mining operations. p.175-187. In C.L. Lin ed., Proceedings of the International Groundwater Symposium, International Association of Hydrogeologists. (Halifax, Nova Scotia, May 1-5).

Morin, K.A., and N.M. Hutt. 1994. MINEWALL Version 2.0: expansion, improvement, and verification of existing code. Draft report for Canadian MEND Program.

Morin, K.A., C.E. Jones, and R.P. van Dyk. 1994. Internal hydrogeologic monitoring of an acidic waste-rock dump at Westmin Resources' Myra Falls Operations, British Columbia. In Third International Conference on the Abatement of Acidic Drainage (these proceedings). http://dx.doi.org/10.21000/JASMR94010355

Morin, K.A., E. Gerencher, C.E. Jones, and D.E. Konasewich. 1991. Critical literature review of acid drainage from waste rock. Report for the Mine Environment Neutral Drainage (MEND) Program.

Morth, A.H., E.E. Smith, and K.S. Shumate. 1972. Pyrite systems: a mathematical model. Contract Report for the U.S. Environmental Protection Agency, EPA-R2-72-002.

Norecol, Dames, and Moore. 1993. Long term kinetic acid generation studies Cinola Project, Queen Charlotte Islands British Columbia [sic]. Report for the British Columbia Acid Mine Drainage Task Force.

Rescan Consultants Inc. 1992. Hydrological and metal loadings study, Phase 1 report. Mine Report for Island Copper Mine, BHP Minerals Canada Limited.

Senes Consultants Limited. 1991. The Reactive Acid Tailings Assessment Program (RATAP.BMT3). MEND Program project.