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# Prediction of water chemistry in mine lakes: The minewall technique

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## Abstract

Water chemistry in mine lakes, derived from open-pit and underground mining, has been studied for more than 30 years. The compilation of this work has led to a predictive technique named 'Minewall', developed for the former Canadian mine environment neutral drainage (MEND) program. Minewall includes procedures for collecting relevant data, interpreting the data, and optional computer modelling of complex scenarios. Key geochemical requirements of Minewall are unit-surface area-production rates, total reactive rock-surface area in a mine, and time-varying reaction-product retention and flushing. Data from several open-pit and underground mines are presented to illustrate the technique. For example, the measured unit-surface area rates of sulphide oxidation and zinc production from rock surfaces span approximately three orders of magnitude. At one site, the rate of physical weathering was equivalent to the rate of chemical weathering, indicating new reactive minerals would continue to be exposed through closure. Also, the case studies indicate that up to 90% of weathering products are retained on the rock surfaces each year, and are thus available for relatively fast release upon closure and flooding of a mine, potentially leading to an acidic mine lake. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

One primary concern for post-mining landscapes is the chemistry of water accumulating in and flowing through open pits and underground workings, collectively called 'mine lakes' in this paper. The water in these mine lakes can be acidic and/or metal-laden due to geochemical processes,

and these conditions can persist for many decades and longer. Because the recovery of post-mining ecosystems around mine lakes is dependent on water chemistry, the predictions of the severity of mine-lake chemistry and its duration are critical.

The detailed prediction of mine-lake chemistry has a relatively long history, reaching back to at least the 1960s. For example, Morth et al. (1972) summarised studies from the 1960s delineating the physical and geochemical processes affecting water chemistry in underground mines. A primary process affecting mine-water chemistry is, of

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course, the release of metals and/or acidity from the walls of the mine. Morth et al. (1972) indicated that this release occurs in three distinct modes, such as diffuse leaching, trickle leaching, and inundation leaching.

Diffuse leaching is generally continuous and represents the release of metal and/or acidity into non-point-source water which slowly and persistently enters the mine, including condensation of water vapour (Morth et al., 1972). For wider applicability, this leaching is renamed, 'regular' release here.

Trickle leaching is the release of metals and/or acidity to point-source water, such as from a borehole or fracture, that occurs seasonally or during storm events. It is renamed, 'occasional' release here.

Finally, inundation leaching represents the release of metals and/or acidity to water which submerges at least part of the mine. This occurs by design only after mine closure. As a result, an inventory of readily leachable and soluble metals and acidity can accumulate in the walls of a mine during operation, awaiting post-mining flooding of the walls. The effects of this 'recently submerged' release can be significant (MacGregor, 1966; Wolkersdorfer, 1996), and also has a parallel in submerging oxidized waste rock (Morin and Hutt, 1997; Morin and Hutt, in press).

## 2. The Minewall technique

The past works of Morth et al. (1972) and others were condensed and extrapolated to all types of mines under a study for the former Canadian mine environment neutral drainage (MEND) project, named 'Minewall' (Morin, 1990; MEND, 1995; Morin and Hutt, 1995, 1997). The Minewall technique recognises that the chemistry associated with water in mines is the result of three basic processes (Fig. 1),

1. the chemical loading brought into a mine by the various sources of water flowing into it;
2. the additional loading provided by the rock exposed on the minewalls and in fractures behind the walls (like the work of Morth et al., 1972), and;

3. the geochemical evolution of the water chemistry during its residence in the mine.

Each of these processes can be the dominant control on chemistry for a particular mine, depending on its unique combination of physical, chemical, and biological characteristics. As a result, all the three must be considered.

During the operation of a mine, the first two processes are represented in Minewall by a basic mass-balance equation. This equation for each concentration in the drained or pumped mine water is relatively simple, using the units of milligram (mg), litres (l), and week (wk),

$$\text{Conc}_m = \frac{\{[\text{Flow}_1 \times \text{Conc}_1] + [\text{Flow}_2 \times \text{Conc}_2] + \dots + \text{MW}_1\}}{\{\text{Flow}_1 + \text{Flow}_2 + \dots\}} \quad (1)$$

where  $\text{Conc}_m$  is the concentration in pumped/draind minewater ( $\text{mg l}^{-1}$ );  $\text{Flow}_x$  is the positive (inflow) or negative (outflow) flow-rate, such as precipitation or groundwater ( $\text{l per week}$ );  $\text{Conc}_x$  is the concentration associated with  $\text{Flow}_x$  ( $\text{mg l}^{-1}$ ); and  $\text{MW}_1$  is the loading ( $\text{mg per week}$ ) from occasional and regular flushing of minewalls.

Eq. (1) assumes that all input  $\text{Flow}_x$ ,  $\text{Conc}_x$ , and  $\text{MW}_x$  are constant, but can easily be adjusted to consider weekly variations in input (Eq. (2)). Also, a negative value for  $\text{Conc}_m$  in

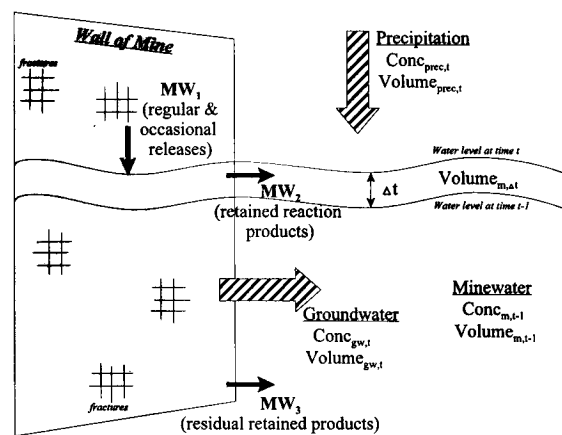


Fig. 1. Schematic diagram of interactions between a minewall and adjacent mine lake after mine closure.

Eq. (1) means there is a net loss of water from the mine, which occurs in some circumstances (Morin and Hutt, 1997).

After mining, when active pumping or draining ceases concentrations in the water filling, the mine can reflect additional effects like the ongoing accumulation of mine water, additional contributions from chemical retention in the minewalls, and the potential for flow reversals. As a result, all three aforementioned processes can be important (Fig. 1). With units of mg, l, and a time step of one week, the general equation for concentrations in mine water during closure is,

$$\begin{aligned} \text{Conc}_{m,t} = & \{[\text{Conc}_{m,t-1} \times \text{Volume}_{m,t-1}] \\ & + [\text{Flow}_{1,t-1} \times \text{Conc}_{1,t-1}] \\ & + [\text{Flow}_{2,t-1} \times \text{Conc}_{2,t-1}] + \dots \\ & + \text{MW}_{1,t-1} + \text{MW}_{2,t-1} \\ & + \text{MW}_{3,t-1}\} \frac{\text{Evol}_{m,t}}{\text{Volume}_{m,t}} \end{aligned} \quad (2)$$

and

$$\begin{aligned} \text{Volume}_{m,t} = & \text{Volume}_{m,t-1} + \text{Flow}_{1,t-1} \\ & + \text{Flow}_{2,t-1} + \dots \end{aligned} \quad (3)$$

where  $\text{Conc}_{m,t}$  is the closure concentration (mg  $l^{-1}$ ) in ponded mine water at current week,  $t$ ;  $\text{Conc}_{m,t-1}$ , is the closure concentration (mg  $l^{-1}$ ) in ponded mine water at previous week,  $t-1$ ;  $\text{Volume}_{m,t}$ , is the volume of ponded mine water at current week ( $l$ );  $\text{Volume}_{m,t-1}$  is the volume of ponded mine water from the previous week ( $l$ );  $\text{MW}_{1,t-1}$  is the loading (mg per week) from occasional and regular release from minewalls;  $\text{MW}_{2,t-1}$  is the loading (mg per week) from recently submerged release from minewalls;  $\text{MW}_{3,t-1}$  is the any loading (mg per week) from the previously submerged minewalls;  $\text{Evol}_{m,t}$  is the factor representing evolution of mine water chemistry between times  $t-1$  and  $t$ ; each element can have a different value.

When there is no accumulation of water in the mine ( $\text{Volume} = 0$ ) and no significant evolution over the time period ( $\text{Evol}_{m,t} = 1.0$ ), Eq. (2) reduces to Eq. (1).

### 3. Flow ( $\text{Flow}_{x,t-1}$ ) and concentration ( $\text{Conc}_{x,t-1}$ ) factors

All  $\text{Flow}_{x,t-1}$  and  $\text{Conc}_{x,t-1}$  in Eqs. (1)–(3) must be known to predict mine-lake chemistry. Most of this required information on flows and concentrations, such as for precipitation and groundwater, can be obtained from routine monitoring of a minesite in any stage of planning, operation, or closure. Also, concentrations in precipitation and evaporation are often negligible and can, thus, be ignored. The remaining  $\text{Conc}_x$  for groundwater flow can come from monitor wells at the minesite. Therefore, most of the data requirements for Minewall assessments can be relatively easily obtained or estimated from normal monitoring data, except the  $\text{MW}_x$  factors and  $\text{Evol}_{m,t-1}$ . Furthermore, because operating mines often monitor flow and chemistry ( $\text{Conc}_m$ ) in mine drainage/pumpage, Eq. (1) can sometimes be solved in reverse to obtain an unknown  $\text{Conc}_x$  or  $\text{Flow}_x$ .

### 4. Minewall factors ( $\text{MW}_x$ )

Again, the primary unknown factors in Eqs. (1)–(3) are often the  $\text{MW}_x$  factors, reflecting loadings from the rock surfaces on and behind the minewalls (Fig. 1). These loadings are considered ‘release rates’ into the mine water, such as 300 mg Ca per week, representing the sum of releases from all relevant areas of the mine. During operation and closure, these rates are determined by three factors, (1) unit-surface area-production rates, (2) total reactive rock-surface area in a mine, and (3) reaction-product retention and flushing. In other words, for one week of time,

$$\begin{aligned} \text{Release rate (MW}_x, \text{ mg per week)} \\ = & \{[\text{Production rate (mg m}^{-2}\text{surface per week)} \\ & \times \text{total rock surface (m}^2\text{)}] \\ & + [\text{Previously retained products (mg)}]\} \\ & \{\% \text{Flushed from rock surfaces}\} / 100\% \end{aligned} \quad (4)$$

Table 1  
Range of minewall production rates ( $\text{mg m}^{-2}$  per week) from five mines

Parameter <sup>a</sup>	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5
Number of stations	6	5	5	3	4
pH (units)	6.43–7.28	4.9–6.1	6.23–7.31	2.15–2.60	4.49–6.39
Alkalinity	21–280	7.0–73	4.8–25	0	0–200
Acidity	1.4–22	3.6–54	–	–	1.6–28
Sulfate	120–2700	48–540	8.9–190	–	3.6–35
Nitrate	0.0082–1.5	0.080–3.2	–	–	0.032–0.11
Aluminum	<0.3	0.013–0.13	0.13–1.1	–	0.0078–2.0
Cadmium	<0.014	0.00095–0.033	<0.01	–	0.0049–0.037
Calcium	41–250	–	9.2–75	–	3.6–120
Copper	0.0086–0.88	0.0087–2.4	0.0089–0.062	–	0.015–1.4
Magnesium	17–530	0.15–3.3	–	–	0.24–9.9
Manganese	0.015–2.1	–	–	–	0.025–1.0
Molybdenum	0.0082–0.36	0.00021	0.0000204	–	$1.7 \times 10^{-5}$ –0.0053
Sodium	1.2–4.2	–	–	–	0.39–2.0
Zinc	0.0022–0.092	0.20–3.9	<0.10–0.17	–	0.073–3.2

<sup>a</sup> All parameters in units of  $\text{mg m}^{-2} \text{ week}^{-1}$ , except number of stations (integer) and pH (pH units).

Unit area-production rates can be obtained for Eq. (4) from 'Minewall Stations' (see, procedure in Appendix A). These stations are relatively simple and inexpensive. Nevertheless, they are effective at allowing reactions to proceed unhindered while preventing removal of reaction products until intended sampling.

Examples of unit area-production rates from Minewall Stations are provided in Table 1. The currently reported range of pH values measured at stations range from 2.2 to 7.3. Also, the rate of physical weathering of the minewalls at mine 1 averaged 1400 mg of particles per  $\text{m}^2$  per week (Table 1), which was generally equivalent to the rate of chemical weathering based on mg of dissolved solids per  $\text{m}^2$  week. As a result, fresh minerals at this mine were continuously being exposed for weathering and leaching. Because unit area-production rates can vary from point to point, a sufficient number of measurements are needed to calculate a representative release rate.

After geochemical reaction rates are obtained for unit surface areas, the next parameter in Eq. (4) is the amount of reactive rock surface. This is not synonymous with the visible or exposed surface within a mine due to fractures in the walls. Fractures are always present in minewalls, occurring naturally and induced by blasting and exca-

vation (Evans, 1987; Toran and Bradbury, 1988; Pusch, 1989; Case Studies 3.2.2-1 and 3.2.2-2 in Morin and Hutt (1997)). These fractures can provide significant additional reactive surfaces. For example, Morth et al. (1972) and others have identified reactive fracture surfaces that extended as far as 15 m from the visible minewalls. Consequently, the fracture surfaces behind the minewalls can provide a much greater reactive surface than that indicated simply by the visible walls.

For example, a minewall, that has (1) spacings for vertical and horizontal fractures of 1 m and (2) oxidation occurring to 10 m behind the wall, will have 41  $\text{m}^2$  of reactive surface for each  $\text{m}^2$  of visible wall (41:1). Based on Minewall studies to date, the average estimated ratio varies from 27:1 to 161:1. Any waste rock, ore rock, tailings, or backfill placed in the mine can add significantly to this reactive surface area (MEND, 1995; see also the example below).

The retained reaction products on the reactive surfaces are released if water flows over and removes them. Because water flow is often intermittent, this leads to the third and last factor in Eq. (4) for estimating  $\text{MW}_x$  (Eqs. (1)–(4)). The Minewall technique recognises that certain percentages of the total reactive-rock surfaces are flushed (1) regularly by precipitation, condensa-

tion, etc., (2) occasionally, such as during snowmelt or a high-precipitation month, and (3) not at all during operation, but soon after submergence. These are, in fact, the three types of 'leaching' delineated by Morth et al. (1972) and discussed above. Studies of open pits to date show that only a few per cent of annual-reaction products are removed regularly, roughly 10–30% is removed occasionally, and 70–90% is retained throughout operation until submergence (Morin and Hutt, 1995). In contrast to pits, underground mines typically have lower percentages retained (5–50%) during operation (Morth et al., 1972; Morin and Hutt, 1997). At closure, the recently-submerged category can significantly affect water chemistry as the mine-lake level rises and flushes reaction products accumulated over the years from flooded surfaces (Fig. 1). For walls above the flooded level, the first two categories (regular and occasional) continue to play an ongoing role in mine-lake chemistry for as long as the mine exists.

### 5. Evolution of mine-lake water ( $Evol_{m,t}$ )

Once the chemical loadings from the inflows and minewalls have been added to the mine waters, water chemistry may reflect the unaltered combined loadings ( $Evol_{m,t} = 1.0$  in Eq. (2)) or may begin to evolve from the combined loadings due to various physical, chemical, and biological mechanisms ( $Evol_{m,t} < > 1.0$  in Eq. (2)). This evolution is one of the three basic processes affecting mine-lake chemistry and, in some cases, can significantly alter chemistry from that determined by mass-balance and  $MW_x$  factors. For example, mineral precipitation/dissolution, controlled by equilibrium or kinetic processes, can greatly increase or decrease concentrations in mine-lake water. Also, redox reactions can change concentrations of some aqueous species through transformation to other ions. For example, sulphate-reducing bacteria can reduce sulphur from sulphate ( $SO_4^{2-}$ ) to sulphide ( $S^{2-}$ ).

There are also physical mechanisms that can affect mine-lake chemistry. For example, 'thermoclines' separate water layers with different temperature and 'chemoclines' separate those with

different chemistries (Wetzel, 1983). Due to seasonal changes in temperature and climate, unstable thermal stratification and internal waves can arise (Stevens et al., 1994; Stevens and Lawrence, 1995) and lead to some or all of the water layers mixing vertically ('turnover'). In turn, concentrations at a particular location in the mine lake can change significantly.

### 6. Two examples of Minewall simulations

A simple example of a Minewall simulation involved the delineation of rock units, static-test parameters (Table 2), and unit area-production rates from stations. The simulation was calibrated to existing monitoring data from the pit to obtain percentages of surfaces flushed at various intervals. The resulting prediction indicated that, although most of the walls were net acid generating and would release stored acidity upon flooding, pH would not be acidic through closure (Fig. 2). This was a consequence of inflowing background groundwater with sufficient alkalinity to offset the release of retained acidity from the rock (Morin, 1990). This dominance of pit-water pH by inflowing groundwater has been noted at other minesites (MEND, 1995).

Another simple example illustrates the value of Minewall in optimising chemical controls. Minewall Stations in an existing underground mine showed that the walls could only account for 2–3% of metals and acidity in the water. A review of historical records revealed that approximately 40 000 t of broken massive sulphide ore was left on some levels. Simple estimates of the particle-surface areas of this ore indicated that it could account for most of the observed acidity and metals. Therefore, control plans focused on removing or encapsulating the broken ore rather than the walls of the mine.

### Appendix A. Installation and operation of monitoring stations for Minewall investigations (from Morin and Hutt (1997))

Equipment (for each station).

Table 2  
Partial input data for the simulation of the main zone pit at equity silver mines<sup>a</sup>

Parameter	Rock unit		
	# 1	# 2	# 3
Rock type	Gabbro	Volcanics	Volcanics
Net neutralization potential from acid–base accounting ( $t$ CaCO <sub>3</sub> per 1000 $t$ )	>0.0	–40 to 0.0	<–40
Orientation on pit wall	Vertical	Vertical	Vertical
Exposed surface area (m <sup>2</sup> )	315000	234000	214000
Sloping walls–percentage of total area	35%	35%	35%
Sloping walls–angle from horizontal (degrees)	70	70	70
Exposed acid-generating sulfur (g S per m <sup>2</sup> )	48	64	144
Exposed neutralization potential (g CaCO <sub>3</sub> per m <sup>2</sup> )	225	100	25
Reactive surface (m <sup>2</sup> ) for each m <sup>2</sup> of pit wall	21	41	41
<i>Fracture flushed</i>			
Percentage flushed monthly	28%	28%	28%
Percentage flushed once a year	2%	2%	2%
Percentage not flushed during operation	70%	70%	70%

<sup>a</sup> Adapted from Morin (1990).

1. Three meters of 90°-bent, flexible plastic bathtub edging.
2. Two tubes of pure silicon bathroom sealant (must be pure silicon).
3. One sheet of clear plastic 1 × 1 m.
4. Eight black metal clasps often used for holding unbound reports.
5. Distilled water (1 l) in a squeeze bottle which allows the direction and pressure of water to be controlled.

Installation procedure (see Fig. 3).

1. Select a relatively flat surface of rock, preferably with no surface fractures, measuring no more than 1 m by 1 m.
2. Mark the intended perimeter of the station on the surface with a pencil, with three, four, or five sections of edging.
3. The lowest, or bottom, limb must slope downwards from horizontal so that all water caught on it will drain in one direction for collection and later analysis.
4. Cut the plastic edging to the length required for each limb.
5. Install each limb by using pure silicon sealant as glue.
6. Ensure silicon sealant fills all open spaces between the edging and the rock surface so

that no water can pass through.

7. Ensure each limb overlaps so that no gaps exist at any junction.
8. Ensure the upper limb(s) will divert water around the sides of the station so that the water will not flow over the isolated area.
9. With 1 l of distilled water, wash the entire isolated surface within the edging, rinsing out

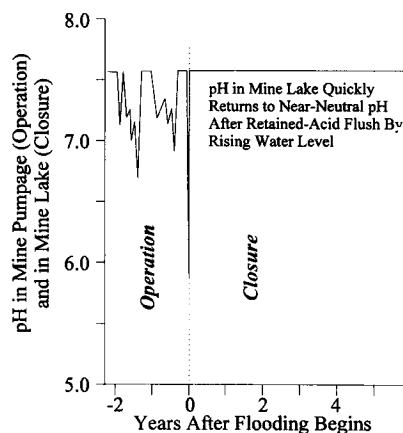


Fig. 2. Predicted pH from a minewall simulation in drainage (during operation) and in the mine lake (after closure).

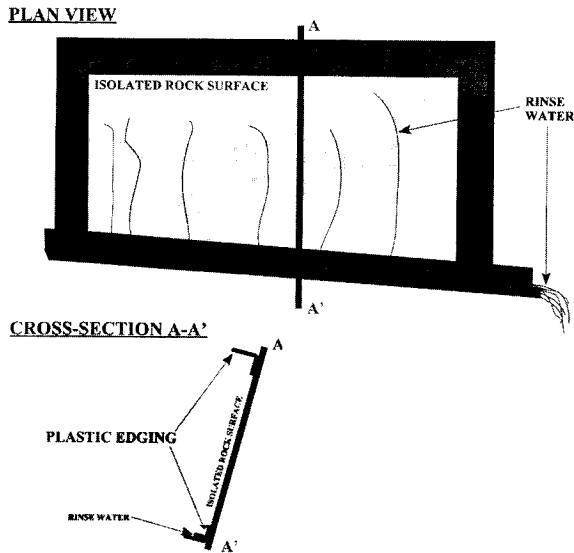


Fig. 3. Example of a Minewall Station, plan view and cross-section (from Morin and Hutt (1997)).

any loose rock/dust and ensuring all water is caught by the edging and directed to the bottom limb where the water can then be caught in a bottle.

10. Cut the clear plastic sheet to extend 2 cm over each limb, then loosely attach the plastic sheet with the metal clasps, ensuring the plastic sheet does not touch the rock surface but prevents all precipitation or runoff from reaching the isolated rock surface.

#### Regular sampling.

1. Carefully remove the plastic sheet and place it somewhere clean and dry.
2. Inspect the station for loose edging and broken seals against the rock; repair any problems after sampling (below), but avoid losing rinse water through any broken seals.
3. Record a note if there is any condensation and if any water may have condensed and trickled out of the station between sampling events.
4. Place a calibrated collection bottle at the downstream (outflow) end of the lower limb (trough) to catch all subsequent rinse water.
5. With a calibrated squeeze bottle, spray at least 200 ml onto the isolated rock surface to rinse the entire area thoroughly; use as little water as possible; it is important to catch all rinse

water in the collection bottle, record the volume of water sprayed on the rock.

6. Record the amount of water recovered in the collection bottle.
7. Analyse the water in the collection bottle like any other water sample, including pH, acidity, alkalinity, sulphate, dissolved metals, and total metals, as desired.
8. As a quality-assurance procedure for one round of sampling, also filter a similar volume of the distilled water through a 0.45  $\mu\text{m}$  filter, then analyse like all other water samples.

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