

Scaling Geochemical Loads in Mine Drainage Chemistry Modeling: An Empirical Derivation of Bulk Scaling Factors

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ABSTRACT

The development of water quality predictions for seepage from mine waste facilities is an integral component of the environmental assessment of minesites. Direct scaling of geochemical loads measured by laboratory kinetic tests such as humidity cells relative to the mass of a full-scale mine waste facility will lead to concentration predictions for mine drainage that are unrealistically high for many dissolved constituents. As a result, “scaling factors” are applied to account for discrepancies in parameters such as grain size, temperature and water/rock ratio between the laboratory experiments and the field scale waste rock facilities.

In this study, waste dump seepage chemistry data from two minesites are compared to upscaled, representative laboratory test cell leachate data in an attempt to better constrain bulk scaling factors. Additionally, larger scale field experimental data (field bins) were considered as an intermediate scaling step.

It was observed that geochemical loads for major ions from the sites are commonly more than two orders of magnitude lower than those predicted by direct scaling of laboratory kinetic test loads, yielding bulk scaling factors of <1%. In these models, many dissolved trace ions that may be of concern in mine drainage (*e.g.*, As, Cu, Cd, Se, *etc.*) may still be significantly overpredicted if the model is calibrated to major ions, likely as a result of solubility limits and other attenuation mechanisms. Unlike loading rates, concentrations in field bin and waste dump drainage were commonly found to be on the same order of magnitude for both neutral and acidic sites suggesting that geochemical equilibrium may be attained at relatively small scales in waste piles, highlighting the importance of intermediate-scale field experiments.

INTRODUCTION

One of the biggest environmental concerns related to modern mining is the release of acidity and metals into the surrounding environment in response to water-rock interaction occurring in sulfidic waste rock storage facilities. Drainage quality predictions conducted as part of geochemical studies incorporate small- to intermediate-scale kinetic experiments that are carried out on mine rock and tailings. These tests provide insight into the reaction mechanisms, lag time for onset of acid rock drainage (ARD), and metal leaching (ML) behavior. A major challenge associated with the application of kinetic test results is the extrapolation of leachate chemistry to predict full-scale minesite drainage chemistry even when waste rock compositions, tonnages and site water balance are constrained. A common approach is to convert laboratory kinetic test leachate concentrations into a geochemical loading rate (*e.g.*, mg/kgrock/week) which is then upscaled to the tonnage of the waste dump to predict drainage quality:

$$\text{Predicted Concentration} = \frac{\text{HC Load} \times \text{Time} \times \text{Mass of Rock in Dump}}{\text{Volume of Infiltrating Water}} \quad (1)$$

It has long been recognized that the resulting loads commonly strongly overestimate actual geochemical loads seen in drainage from waste dumps (Morin & Hutt, 1994; Malmström *et al.*, 2000). This is largely attributed to discrepancies in geochemical and physical conditions between laboratory kinetic reactors and full-scale waste dumps, including but not limited to:

- water-rock interaction (contact);
- gas transport and oxygen content;
- reactive grain size distribution (and associated occlusion of reactive minerals);
- temperature (both sulfide and carbonate dissolution reactions are temperature-dependent).

In an attempt to account for the variable geochemical regimes, many authors have begun introducing scaling factors based on theoretical assumptions and field observations (Malmström *et al.*, 2000; Neuner *et al.*, 2009; Kempton, 2012). In theory, a scaling factor (generally <100%) is assigned to each of the lab-to-field discrepancies identified and multiplied by the upscaled load. Understandably, depending on the type of waste material and the climatic conditions at a minesite, the sometimes inter-related individual scaling factors vary widely in practice (Kempton, 2012). A so-called bulk scaling factor, defined as the product of all individual scaling factors can be calculated empirically where laboratory kinetic and waste drainage chemistry data are available, however a comprehensive database for different deposit types and climate conditions is missing. Nevertheless, several studies have addressed this topic and bulk scaling factors on the order of 5 to 60% have been reported (*e.g.*, Andrina *et al.*, 2012; Hanna & Lapakko, 2012; Morin & Hutt, 1994).

This paper presents waste rock leachate and drainage chemistry results from reactors of various scales. The waste rock is associated with two minesites located in semi-arid regions, one with neutral and the other one with acidic drainage. The focus of this study is the dependence of geochemical loading rates on the scale as well as the variability of geochemical behavior between different species.

METHODOLOGY

Humidity cell experiments for materials from both sites were conducted according to the standardized method outlined in ASTM D5744 (2010) applying three days of dry air and three days of moist air flow to each 1 kg of waste rock followed by flooding with deionized water (500 mL) and leachate sampling on day seven. Column experiments on waste rock from Site B are made up of 5 kg of material with variable irrigation volumes (300-500 mL) applied as a trickle leach at 1 mL/min every two weeks. Between sampling cycles the cells were exposed to dry air allowing for a better representation of the mine-specific climate.

Field kinetic experimental procedures are consistent between the two minesites with field bins containing 150-200 kg of waste rock which are either flushed naturally by rain water or, in case of longer dry periods, are manually irrigated with deionized water. As the leachate sample is taken, the outflow volume is recorded to allow the calculation of geochemical loads.

RESULTS AND DISCUSSION

Static test results of the various waste rock materials and WRSA dimensions for Sites A and B are given in Table 1.

Table 1 Selected static test results and WRSA dimensions for the studied minesites

		Site A		Site B
		<i>Oxide</i>	<i>Sulfide</i>	<i>Diorite</i>
Total S	%	0.82	2.9	0.22
Sulfide S	%	0.020	2.5	0.030
NP	<i>kg CaCO₃/t</i>	-1.0	-1.1	88
NPR		<0	<0	40
WRSA tonnage	<i>Mt</i>	57	38	2.7
WRSA footprint	<i>ha</i>	91		9.9

Notes: chemical results are median values; NP = bulk neutralization potential; NPR = net potential ratio.

Site A (acidic drainage)

Site A is a porphyry-gold deposit located in a semi-arid environment with an average annual precipitation of 550 mm. The waste rock storage area (WRSA) contains rock from volcanic intrusions and volcanoclastic sediments of intermediate to felsic composition. Sulfide S content and associated drainage chemistry is predominantly associated with the degree of natural weathering which led to the subdivision of waste rock into two main categories, namely Oxide and Sulfide materials. The former is generally devoid of sulfide minerals, but contains considerable amounts of acid-producing sulfate salts such as jarosite and alunite. Sulfide waste rock contains up to 7.6% of sulfide S with a median value of 2.5% (Table 1), mainly in the form of pyrite. Both material classes show little to no carbonate mineralization, and therefore have little capacity for acid-neutralization. All waste rock is stored within the same facility with Oxide rock used as cover material for the highly reactive Sulfide waste. Figure 1 shows a tertiary diagram of major elemental ratios in Site A WRSA drainage compared to Sulfide and Oxide humidity cell leachates. This plot illustrates the

mixed nature of the waste dump with the influence of Sulfide waste material becoming progressively more important over time. Due to the mixed nature of the WRSA, certain assumptions and data adjustments were made with respect to the calculation of geochemical loads:

- At the time of WRSA drainage collection the ratio of Oxide to Sulfide rock was set to 60% to 40%, consistent with the waste production schedule provided by the client;
- All flows contacting the WRSA are captured by the flow measurements at the seepage collection pond.

WRSA geochemical loading rates were calculated for a 64 week duration extending from September 2011 to December 2012 (construction of the WRSA began in 2010). Selected major ion and minor/trace ion loads are compared to the loading rates derived from kinetic experiments in Figure 2. In this plot, both field bin and humidity cell loads are normalized to the loads derived for the WRSA seepage to calculate an “exceedance factor”:

$$\text{Exceedance factor} = \text{Kinetic test load} / \text{WRSA load}$$

The humidity cell exceedance factors range from 578 (Na) to ~52,000 (As), corresponding to bulk scaling factors of 0.17% to 0.002% (calculated as the inverse of the exceedance factor). These exceedance factors are greater than the field bin exceedance factors which range from 29 to ~24,000, for all parameters except arsenic. The latter is the only species showing a higher load in field bin versus humidity cell leachates. Greater exceedance factors for the humidity cells are consistent with

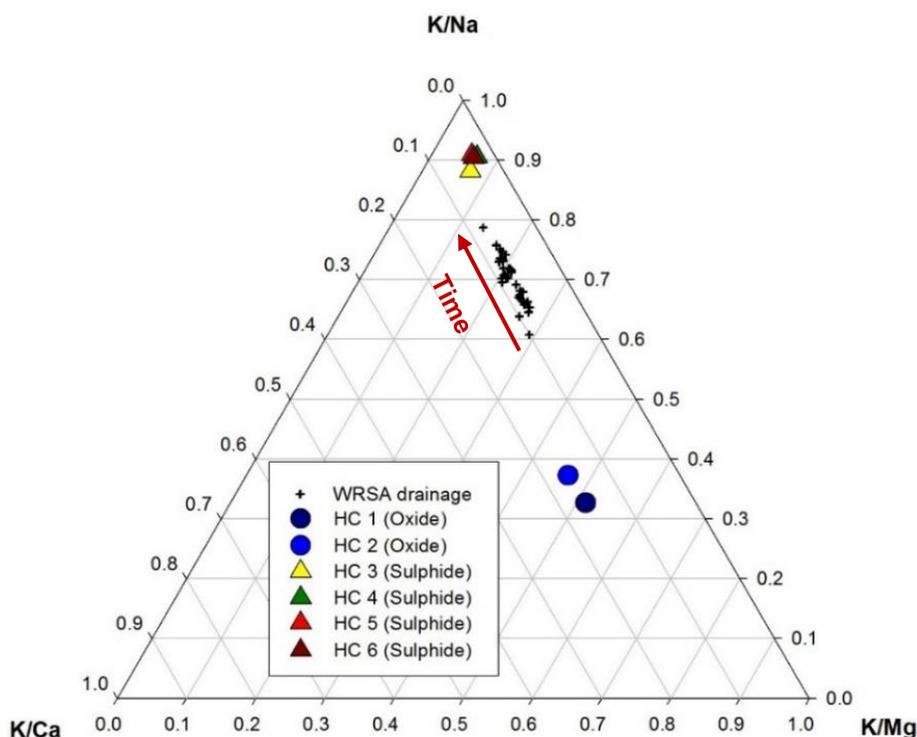


Figure 1 Ternary diagram showing the major elemental ratios in humidity cell leachates versus WRSA drainage for Site A

the greater scale differential between humidity cells and the WRSA compared to field bins versus WRSA.

Humidity cell exceedance factors for the major ions are typically lower than trace ion loads ranging from ~600 to ~1,000 (median bulk scaling factor of 0.15%) not including Fe and K (Figure 2). The latter species display higher exceedance factors around or greater than 5,000 indicating that they are being attenuated in WRSA drainage relative to humidity cell leachates. Under the pH conditions measured in the WRSA drainage, geochemical modeling using PHREEQC (Parkhurst & Appelo, 1999) suggests that the most likely solubility control for Fe and K is the mineral jarosite, which was also commonly identified in Oxide waste rock. The median humidity cell based bulk scaling factor for the shown minor and trace ions is 0.02%, almost an order of magnitude lower than that calculated for other major ions.

As a sensitivity analysis and to account for a conservative case in which the WRSA constantly produces a pH in the range of that seen in the latter stages of the Sulfide humidity cell experiments, the worst geochemistry (pH 3.2) recorded at the seepage collection pond was applied to the same drainage volume over the entire modeling period (64 weeks). In this scenario the median bulk scaling factor for major ions (SO₄, Na, K, Ca, Mg) increases to 0.41%, while the bulk scaling factor for minor and trace ions is 0.13%, still well below bulk scaling factors reported by other workers.

Several species in waste rock seepage can be expected to become saturated when a certain scale (or water/rock ratio) is reached. Therefore, in addition to assessing geochemical loads, it is crucial to also compare concentrations measured in leachate versus seepage waters. In Table 2, the range of field bin leachate concentrations is listed along with the median Site A WRSA drainage concentration for episodes of comparable pH (pH = 3.0 – 3.3). Of the presented parameters, only Al, Cd, and Cu exceed the maximum concentrations observed in field bin leachates but fall within a factor of three of the latter. The remaining species are within the range observed in field bin leachates suggesting that solubility limits control their concentrations.

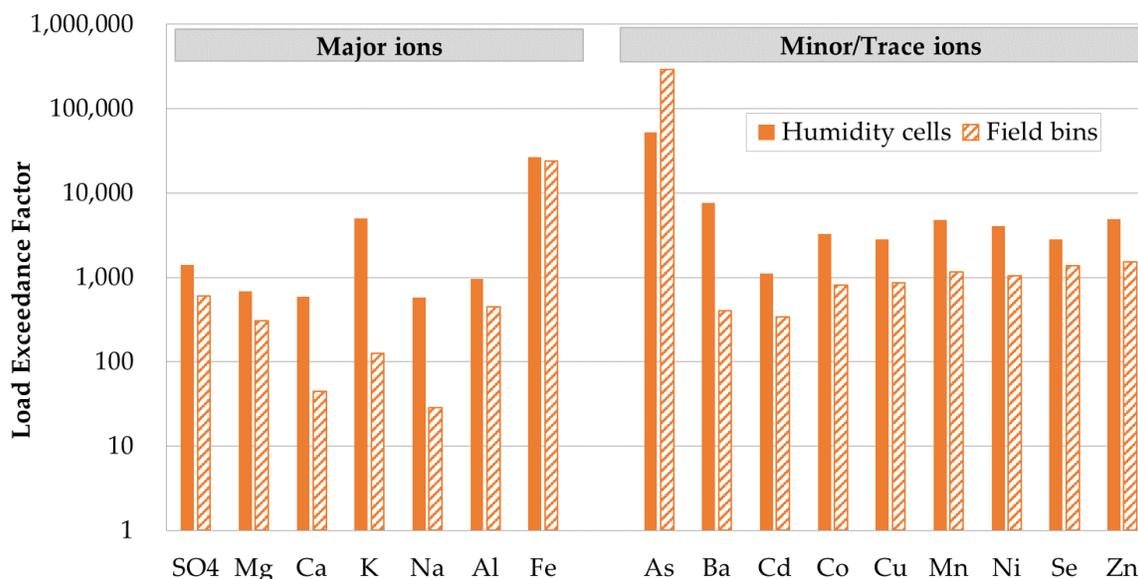


Figure 2 Exceedance factors (relative to WRSA drainage) in humidity cell and field bin leachates for acidic Site A

Table 2 Comparison of the range of field bin leachate concentrations with WRSA drainage chemistry at Site A

	SO ₄	Mg	Ca	Na	K	Al	Fe	As	Ba	Cd	Co	Cu	Mn	Ni	Se	Zn
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
FB (min)	628	34	66	12	10	32	22	0.083	0.070	0.19	3.3	0.33	18	3.2	0.0050	30
FB (max)	2140	168	238	29	13	67	59	0.19	0.19	0.53	4.2	1.5	38	4.7	0.013	89
WRSA	2080	111	194	19	7.1	177	55	0.029	0.067	1.6	1.2	3.3	12	1.1	0.0020	42

Notes: FB = field bin; WRSA drainage concentrations indicated in bold exceed the maximum field bin leachate concentration.

Site B (neutral drainage)

Site B represents a porphyry-copper deposit located in a semi-arid environment and hosted in a complex igneous system of mafic to intermediate plutonic and volcanic rocks. Several hybrid units comprising the major intrusions and volcanic rocks were identified near contacts. Compared to Site A, the sulfur contents at Site B are low with median sulfide sulfur concentrations of 0.22% (Table 1). Carbonate neutralization potential is abundant (median = 29 kg CaCO₃/t) and additionally it was identified that reactive silicate NP is present (median bulk NP = 88 kg CaCO₃/t; Table 1). Overall, waste rock from this site is not expected to generate net acidity, however species that form oxyanions under neutral conditions (*e.g.*, As, Se) may still be mobile in waste rock drainage. Geochemical loads released by humidity cells and their duplicate columns were compared against field bin leachate data (same lithology; no duplicates) and site pore-water from waste rock that is primarily made up of the same dioritic waste rock.

Seepage analyses from the WRSA were obtained through two monitoring wells that were installed at two different depths within a backfilled pit. Sampling depths are both below the water level, however geochemical analyses suggest that the water is sufficiently oxic to be representative of oxidizing pore-water chemistry. Geochemical loading from Site B WRSA was calculated based on the following assumptions:

- Tonnage: only the non-saturated rock (the upper 12 m) stored in the backfilled pit will contribute to sulfide oxidation, yielding a tonnage of 2.7 Mt;
- Flows: all infiltration into the waste pile (27 mm/yr) will be available for reaction.

Figure 3 shows the exceedance factors of geochemical loading rates calculated for humidity cells (1 kg), duplicate unsaturated columns (5 kg), and field bins (~150-200 kg) relative to the inferred loads from the WRSA at pH-neutral Site B. Loading rates from humidity cells are higher than or similar to those in column leachates. The discrepancy is highest for Al and Fe, suggesting that the attenuation of these two species under neutral conditions is already effective at small scales. The fact that geochemical loads calculated for several species in field bin leachates are similar to or even higher (exceedance factor < 1) than those in the WRSA pore-water suggests that assumptions made for WRSA loading calculations are conservative. This is likely a result of the poorly constrained water balance at this site and/or the fact that field bins were manually irrigated several times, likely increasing the overall load in this climatic setting. Consequently, exceedance and bulk scaling factors presented for Site B in the following should be considered semi-quantitative.

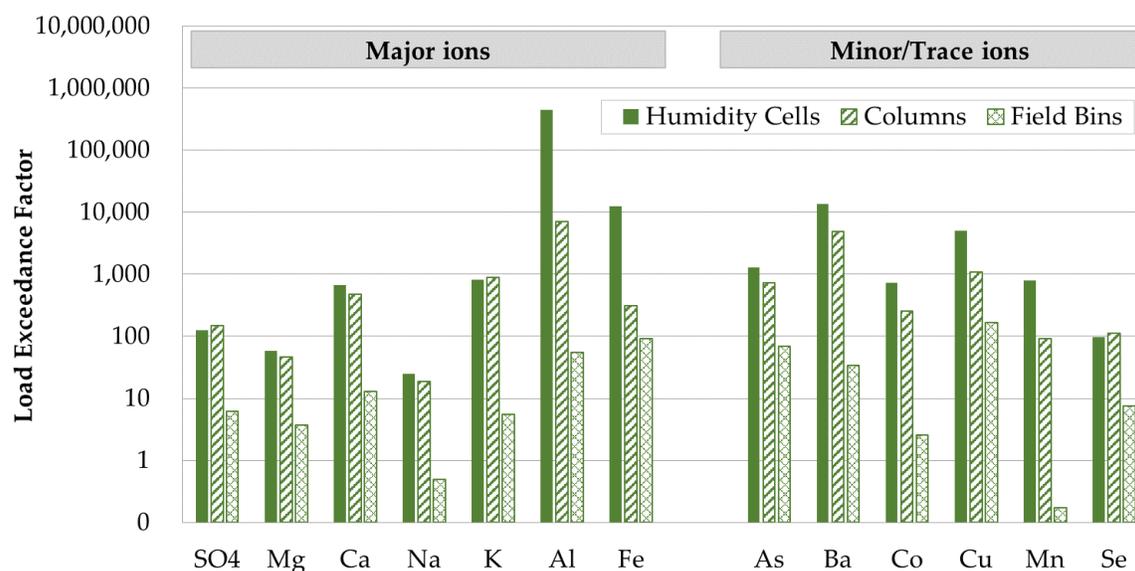


Figure 3 Exceedance factors (relative to WRSA drainage) in humidity cell, column and field bin leachates for neutral Site B

The discrepancy between major ions and trace ions is not as apparent as for Site A, which is likely a result of the different attenuation mechanisms occurring at neutral pH. For example, exceedance factors for laboratory kinetic experiments vary by more than three orders of magnitude for major ions ranging from 25 (Na) to ~444,000 (Al) (Figure 3). Excluding Fe and Al, which are known to be highly immobile under circum-neutral pH, a median bulk scaling factor of 0.8% was calculated. It should be noted that due to the high gypsum content observed in Site B waste rock, Ca and SO₄ are unlikely to behave conservatively. For the shown minor and trace ions, the calculated bulk scaling factor is 0.1% suggesting that, with few exceptions (*e.g.*, Se), scaling to major ions would generally overestimate predicted concentrations for these species in site drainage.

As for Site A, in addition to the geochemical load analysis, selected dissolved concentrations measured in field bin leachates are compared to the WRSA drainage chemistry in order to shed light on possible solubility controls occurring at different scales (Table 3). Na and Mn from the WRSA exceed five times the maximum concentrations in field bin leachates, while sulfate, Mg, K, and Co only slightly exceed the range of field bin leachate concentrations. The very high Na and Mn values may be explained by the impact of blasting residues and the development of suboxic conditions in the backfilled pit, respectively. The fact that many dissolved species fall within the range of field bin leachate concentrations suggest that attenuation mechanisms are active and equilibrium conditions are partly reached at relatively small scales.

Table 3 Comparison of the range of field bin leachate concentrations with WRSA drainage chemistry at Site B

	SO ₄	Mg	Ca	Na	K	Al	Fe	As	Ba	Co	Cu	Mn	Se
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
FB (min)	42	6.9	15	1.2	4.2	0.001 0	0.01 0	0.001 6	0.009 4	0.0001 0	0.006 9	0.00005 0	0.003 5
FB (max)	103 0	92	277	4.4	21	0.015	0.03 0	0.047	0.067	0.0005 0	0.12	0.0089	0.042
WRSA	172 0	296	239	151	43	0.002 2	0.01 0	0.008 1	0.031	0.0014	0.004 6	0.086	0.041

Notes: FB = field bin; WRSA concentrations shaded indicated in bold and with a border exceed the maximum and five times the maximum field bin leachate concentrations, respectively.

CONCLUSIONS

Leachates from laboratory and field kinetic tests were compared to WRSA seepage at two different sites, one producing acidic and the other one with neutral drainage. The main findings from this study are summarized below:

- In order to predict WRSA seepage concentrations at Site A (acidic drainage) bulk scaling factors are <1% (based on humidity cell loads) would have to be applied. These scaling factors are significantly lower than those reported previously, commonly using major ion concentrations for model calibration purposes. Overall, bulk scaling factors for major ions tend to be higher than those calculated for minor/trace parameters, unless major ions are solubility-controlled under acidic conditions (*e.g.*, K and Fe by jarosite). This highlights the importance of differentiated water quality modeling for specific ions;
- Bulk scaling factors calculated for the neutral Site B, excluding Fe and Al, vary between 0.01% and 4% where major ion scaling factors are generally higher (median = 0.8%) than those calculated for minor/trace ions (median = 0.1%). Field bin loading rates that are on the same order of magnitude or even lower than calculated WRSA pore-water loads suggest that assumptions made for the calculation of WRSA loads are conservative and bulk scaling factors for this site are likely lower;
- For both sites, many species appear to be solubility-limited at a scale of field bin experiments (150-200 kg), which is a factor that should be accounted for in water quality prediction modeling.

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