POST-MINING GROUNDWATER CHEMISTRY AND THE EFFECTS OF IN-PIT COAL ASH DISPOSAL: PREDICTIVE GEOCHEMICAL MODELING BASED ON LABORATORY LEACHING EXPERIMENTS

by

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ABSTRACT

Laboratory leaching tests including 10:1 and 40:1 water to sediment ratios and saturated-paste extracts, have been used to determine the salt yielding properties of overburden materials as well as coal ash. This salt yield data, expressed as soluble salt in the appropriate water to solids ratio for field conditions, can be used to predict the salinity and composition of spoil groundwater, and the effects of coal ash disposal on spoil groundwater chemistry. The concentration of ionic species at varying sediment to water ratios is computed using the aqueous geochemical model PHREEQE, which allows consideration of mineral solubility constraints (particularly calcite, dolomite and gypsum), various partial pressures of carbon dioxide, and ion exchange.

The predictive model has been tested at three mine sites in central Alberta, with ash disposal considered at two sites. There is good agreement between the predicted and observed spoil groundwater chemistry at Diplomat Mine (mainly glacial drift overburden), Vesta Mine (mixed Horseshoe Canyon Formation bedrock and drift overburden) and Highvale Mine (mixed Paskapoo Formation bedrock and drift overburden). Disposal of coal ash in mine pits at Diplomat and Vesta Mines is predicted to increase the total dissolved solids in the spoil groundwater to 10,300 mg/l above a background of 5000 mg/l at Diplomat Mine and to 10,500 mg/l above a background of 6500 mg/l at Vesta Mine. The predicted groundwater composition and salinity for ash in spoil at Vesta Mine is in excellent agreement with the composition and TDS of 10,383 mg/l observed in a well installed in an ash site at Vesta Mine.

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INTRODUCTION

The surface mining of coal has a significant impact on the quality of groundwater in and adjacent to mined areas. In almost all cases groundwater in reclaimed areas is more saline than the pre-mining groundwater, and is of different composition (Trudell and Faught, in prep.; Van Voast, 1982; Williams et al., 1983). In order to make planning decisions, particularly in terms of groundwater resource potential and long-term soil salinization in reclaimed areas, it is desireable to predict post-mining groundwater chemistry based on parameters from the pre-mining setting.

METHODOLOGY

The model for predicting post-mining groundwater chemistry presented in this paper has three components: (1) Quantification of soluble salts in overburden materials by laboratory leaching experiments; (2) Production of hypothetical 'spoil' material based on overburden characteristics; (3) Consideration of geochemical processes within resaturated 'spoil' material by means of the aqueous geochemical model PHREEQE (Parkhurst et al., 1980).

Overburden Characterization

The soluble salt producing characteristics of overburden materials were determined by two types of leaching tests; a 10:1 (water:sediment) extract, and a saturated paste extract. For each type of test, the cumulative frequency distribution of electrical conductance (EC) in the extract was used as the basis for characterizing the salinity of overburden materials. Small groups of samples corresponding to various EC percentiles were selected to represent the observed range of overburden salinity. The average salt yield, expressed in grams of salt per kg of sample was determined for each EC percentile group. This analytical treatment was carried out separately for glacial drift overburden and bedrock overburden, which have been identified as the two principal geochemical units that make up mine spoil (Trudell et al., 1983).

Hypothetical 'Spoil'

Hypothetical 'spoil' is made by combining the salt yield characteristics of drift and bedrock on the basis of the average relative thickness of drift and bedrock in the vicinity of a mine site. In producing this spoil, the porosity is assumed to be 30%, and the density of solid particles 2.65 g/cm^3. Upon saturation with water all of the pore space will be occupied with water, and therefore, 1 L of water will be in contact with 6.2 kg of solid spoil material. Consequently, the soluble salt from 6.2 kg of hypothetical spoil will be available to dissolve in 1 L of water.

Aqueous Geochemical Model

The dissolution of salts in spoil groundwater is subject to the constraints of mineral solubility (mainly calcite, dolomite and gypsum), partial pressure of carbon dioxide (P_{CO_2}, higher than atmospheric) as well as ion exchange. The salts from 6.2 kg of 'spoil' are dissolved (numerically) in 1 L of water, using the aqueous geochemical model PHREEQE to account for these processes. Any soluble salt in excess of the solubility limit of the minerals calcite, dolomite and gypsum is precipitated and the amount precipitated is determined. The partial pressure of CO_2 is fixed at a level characteristic of reclaimed spoil, which has been reported as typically .02 to .06 atm (Wallick, 1983). Ion exchange, primarily Ca^{2+} – Na^+, is approximated based on a modified selectivity coefficient (K') as defined by Parkhurst et al., (1980) where

$$K' = \frac{[Na^+]^2}{[Ca^{2+}]} ,$$

the square brackets indicating thermodynamic activity. This approximation is reasonable under conditions in which the reservoir of ions on the exchanger is very large (and therefore approximately constant) relative to the amount of exchanging ions in the solution. K' values were determined for drift and bedrock overburden on the basis of calcium and sodium activities in groundwater samples from unmined sites. To represent the range of observed K' values in overburden materials a log mean K' value was determined, plus a 'minimum' K' (log mean −2 standard deviations) and a 'maximum' K' (log mean +2 standard deviations) were determined. The ion exchange characteristics of the spoil were then approximated by thickness-weighted average K' values, for each pair (drift and bedrock) of minimum, mean and maximum K' values.

RESULTS

Spoil groundwater chemistry predicted using the geochemical model has been compared with observed groundwater chemistry in reclaimed spoil at three mine sites in central Alberta (Figure 1): Vesta and Diplomat Mines in the Battle River Mining Area (200 km southeast of Edmonton) and Highvale Mine in the Lake Wabamun Mining Area (100 km west of Edmonton). In addition, a predicted range of spoil groundwater chemistry was determined for Paintearth Mine, in the Battle River area.

Vesta Mine

At Vesta Mine the overburden consists of calcareous clay till (drift) and fine-grained near-shore, clastic sedimentary rock of the lower Horseshoe Canyon Formation (Late Cretaceous) in average relative proportions of 0.3733 drift: 0.6267 bedrock. The salt yielding characteristics of the overburden materials are summarized in Table 1, and the parameters used in conducting the modeling are listed in Table 2.

The predicted spoil groundwater chemistry from various EC percentile groups is shown in Figure 2 and summarized in Table 3, compared with the observed spoil groundwater chemistry at Vesta Mine. Of predictions developed from the 10:1 dilution data, an acceptable match was obtained mainly for sample groups corresponding to the 0.1 and 0.5 EC percentiles. Mean and maximum K' values were used in obtaining a match with the observed spoil groundwater chemistry. The predicted total dissolved solids (TDS) concentrations from three samples of this group ranged from 7100 to 7700 mg/L, which corresponds well to the mean TDS of 7443 mg/L observed in the spoil groundwater. Two other 10:1 dilution samples fell in the TDS range from 12700 mg/L to 15500 which compares well with the upper limit of observed spoil groundwater salinity (maximum TDS = 13800 mg/L). The predicted composition, like the predicted salinity, also corresponds well with the mean spoil groundwater composition as well as the high sulfate composition.

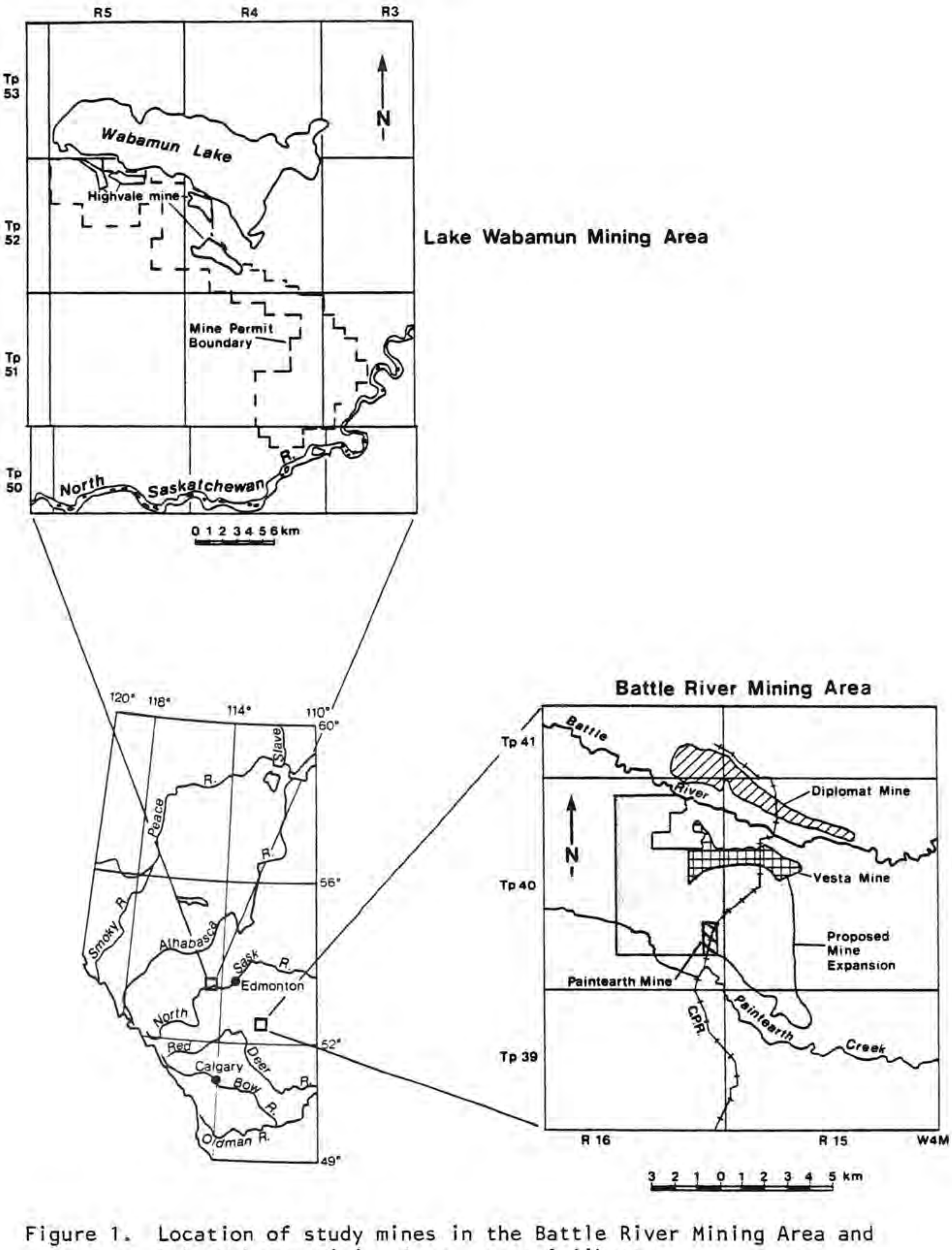

Figure 1. Location of study mines in the Battle River Mining Area and Lake Wabamun Mining Area, central Alberta

Table 1. Summary of Overburden Soluble Salt-Yielding Characteristics

Overburden Type	Method	EC Percentile	# Samples	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{-2}	HCO_3^-	Cl^-	TDS
				Average Salt Yield (g/kg)							
Battle River Area Overburden - Diplomat, Vesta and Paintearth Mines											
Drift	S.E.	.1	4	0.004	0.005	0.006	0.002	0.010	0.024	0.004	0.055
		.5	4	0.029	0.008	0.068	0.026	0.232	0.117	0.008	0.487
		.9	4	1.119	0.040	0.430	0.151	3.726	0.345	0.011	5.821
Bedrock	S.E.	.1	14	0.496	0.036	0.004	0.001	0.233	0.944	0.027	1.740
		.5	12	0.144	0.009	0.014	0.002	0.225	0.287	0.025	0.705
		.9	4	0.964	0.032	0.068	0.011	1.211	0.942	0.120	3.348
Drift	10:1	.1	2	0.295	0.047	0.069	0.052	0.585	0.661	0.027	1.736
		.5	4	1.390	0.163	0.157	0.089	2.953	0.585	0.029	5.366
		.7	5	1.394	0.140	0.274	0.368	3.492	0.569	0.027	6.264
		.9	2	1.570	0.063	0.762	0.561	7.200	0.381	0.019	10.556
Bedrock	10:1	.1	5	0.708	0.040	0.062	0.121	0.262	0.554	0.025	1.772
		.5	6	0.821	0.052	0.038	0.163	0.375	1.292	0.045	2.786
		.7	8	1.144	0.090	0.046	0.100	0.551	1.162	0.022	3.115
		.9	4	1.338	0.093	0.041	0.110	0.952	1.306	0.018	3.858
Highvale Mine Overburden											
Drift	S.E.	.5	4	0.302	0.013	0.010	0.002	0.244	0.540	0.006	1.117
		.7	4	0.111	0.009	0.032	0.007	0.064	0.333	0.016	0.572
		.9	4	0.197	0.008	0.020	0.004	0.743	0.311	0.021	1.304
Bedrock	S.E.	.5	6	0.194	0.018	0.011	0.003	0.095	0.439	0.020	0.780
		.7	6	0.183	0.005	0.003	0.008	0.015	0.292	0.044	0.550
		.9	4	0.230	0.008	0.005	0.002	0.087	0.476	0.037	0.845
Drift	10:1	.1	4	0.248	0.089	0.080	0.017	0.276	0.496	0.059	1.265
		.5	5	0.637	0.084	0.047	0.012	0.595	0.803	0.060	2.238
		.7	3	0.773	0.054	0.031	0.016	0.769	0.763	0.038	2.444
		.9	3	0.652	0.054	0.609	0.161	4.163	0.768	0.136	6.543
Bedrock	10:1	.1	3	0.354	0.049	0.041	0.005	0.197	0.813	0.038	1.497
		.5	3	0.542	0.044	0.034	0.004	0.289	1.208	0.042	2.163
		.7	4	0.695	0.053	0.031	0.002	0.221	1.322	0.057	2.381
		.9	3	0.685	0.075	0.034	0.003	0.171	1.136	0.071	2.175

Note: S. E. = saturation extract
10:1 = 10:1 Dilution test

Table 2. Summary of parameters used in the geochemical model for the prediction of post-mining groundwater chemistry.

Mine	Relative Thickness Drift: Bedrock		P_{CO2} (atm)	Ion Exchange (K') min	mean	max
Diplomat	1.000	: 0.000	0.14	3.006×10^{-3}	0.151	7.621 (Ca-Na)
				-	0.036	0.832 (Mg-Na)
Vesta	0.3733	: 0.6267	0.04	0.424	1.148	8.433
Paintearth	0.000	: 1.000	0.03	-	3.837	8.954
Highvale	0.2381	: 0.7619	0.02	2.928×10^{-3}	0.3042	31.412

Note: '-' indicates value not used

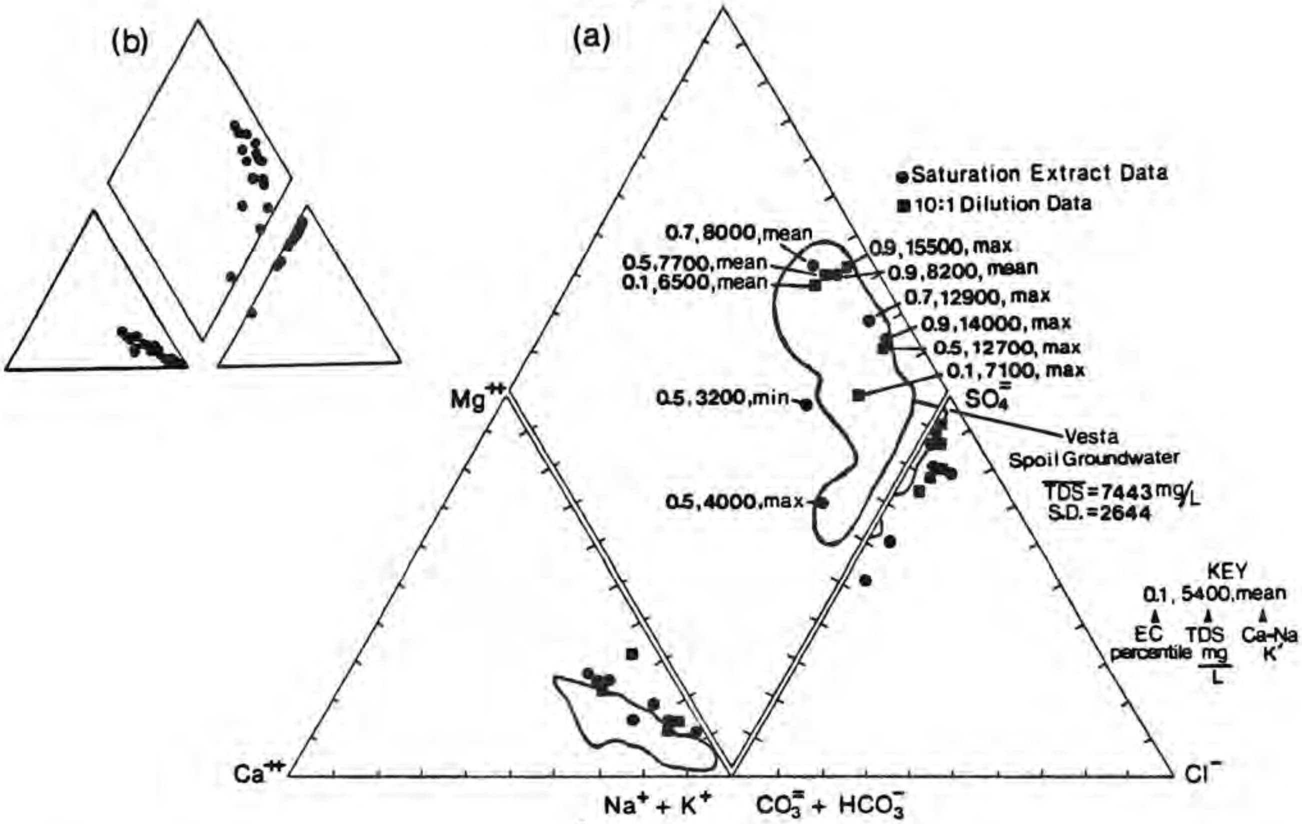

Figure 2. (a) Piper trilinear diagram of calculated spoil groundwater chemistry at Vesta Mine
(b) Observed composition of spoil groundwater samples from Vesta Mine

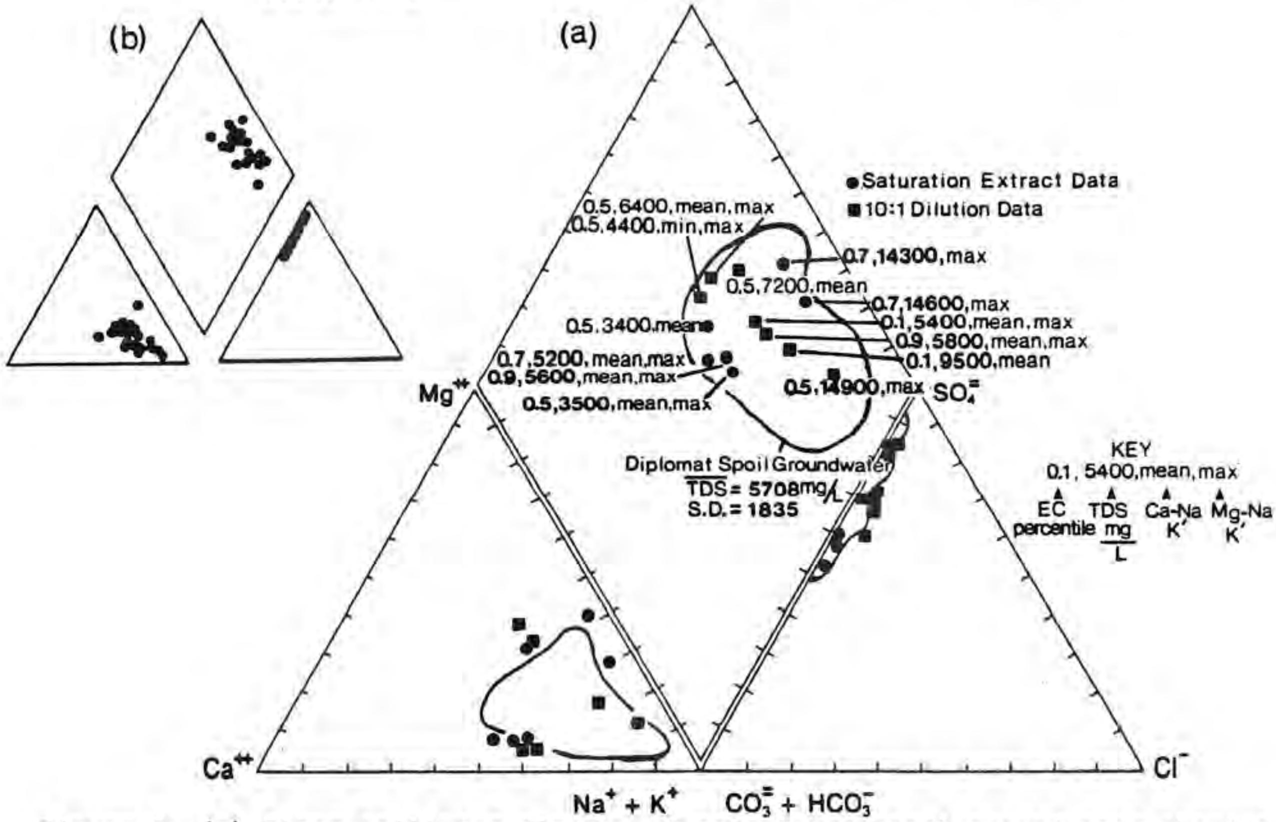

Figure 3. (a) Piper trilinear diagram of calculated spoil groundwater chemistry at Diplomat Mine. Single value for K' refers to Ca-Na K'; two values refer to Ca-Na, Mg-Na K', respectively. (b) Observed composition of spoil groundwater samples from Diplomat Mine

Groundwater chemistry predictions for Vesta Mine spoil based on saturation extract data tend to bracket the observed spoil groundwater composition and salinity. An acceptable match is obtained with sample groups corresponding to the 0.5, 0.7 and 0.9 EC percentiles, and predicted salinities include a lower range (3200 to 4000 mg/L TDS) and upper range (8000 to 14000 mg/L TDS) that correspond to the minimum (4500 mg/L) and maximum (13800 mg/L) observed spoil groundwater TDS concentrations, respectively. Similarly, the predicted composition includes the low-sulfate and high-sulfate range of observed composition. As with the 10:1 dilution, mean and maximum K' values were associated with the best-fit predictions.

TABLE 3

COMPARISON BETWEEN PREDICTED AND ACTUAL SPOIL GROUNDWATER COMPOSITIONS

MINE	PREDICTED RANGE TDS (mg/L)	PREDICTED MEAN TDS (mg/L)	ACTUAL RANGE TDS (mg/L)	ACTUAL MEAN TDS (mg/L)
Diplomat	3,400 - 14,600	5,840	2,038 - 12,766	5,708
Vesta	3,200 - 15,500	7,425	4,508 - 13,805	7,443
Paintearth	4,000 - 9,800	7,400	---	---
Highvale	2,000 - 6,900	4,740	1,219 - 6,855	3,668

Diplomat Mine

At Diplomat Mine the overburden is almost entirely made up of calcareous clay till that is typical of the Battle River mining area. Consequently, only the salt yielding characteristics of the drift leach-test samples were considered for the prediction of spoil groundwater chemistry at Diplomat Mine. The overburden salt-yield characteristics for Diplomat Mine are summarized in Table 1, and the parameters used for the geochemical model are listed in Table 2.

Predictions of groundwater chemistry based on 10:1 dilution data match the observed mean composition of spoil groundwater at Diplomat Mine, and as at Vesta Mine include the mean to upper range of observed salinity (Table 3 and Figure 3). The 0.1 and 0.5 percentile groups of the 10:1 dilution samples best match the observed concentrations, and predicted TDS values of 5400 to 6400 mg/L and 9500 to 14900 mg/L correspond to actual mean (5708 mg/L) and maximum (12766 mg/L) TDS concentrations, respectively, in groundwater at Diplomat Mine. Because of the relatively large amount of soluble magnesium in the leach test extracts of drift materials, in several cases it was necessary to consider Mg^{2+} – Na^{+} exchange in addition to Ca^{2+} – Na^{+} exchange to best match the observed composition and salinity. The procedure for considering Mg^{2+} – Na^{+} exchange was identical to that used for Ca^{2+} – Na^{+} exchange, i.e. based on K' values determined from unmined drift groundwater samples. Mean and maximum Ca^{2+} – Na^{+} K' values, together with maximum values of K' for Mg^{2+} – Na^{+} exchange, were used in arriving at the predicted groundwater chemistry.

The pattern of predicted spoil groundwater chemistry based on saturation extract data is essentially the same at Diplomat Mine as was found at Vesta Mine; that is, the predicted values bracket the observed composition and salinity as illustrated in Figure 3, and saturation extract sample groups corresponding to 0.5, 0.7 and 0.9 EC percentiles match the upper and lower range of sulfate composition in the observed groundwater composition. Also, the predicted salinity ranges, from 3400 mg/L to 5600 mg/L TDS and from 14300 to 14600 mg/L TDS correspond reasonably well to the minimum (2000 mg/L) and maximum (12766) observed TDS concentrations. As with the 10:1 dilution, mean and maximum Ca^{2+} – Na^{+} K' values and maximum Mg^{2+} – Na^{+} K' values were used in the predicted groundwater chemistries.

Highvale Mine

The overburden at Highvale Mine in the Lake Wabamun mining area consists of glacial drift (silt, clay and till) and continental, clastic sedimentary rock of the Paskapoo Formation (Upper Cretaceous-Paleocene) in relative proportions of 0.2381 drift:0.7619 bedrock. The salt yielding properties of overburden materials at Highvale Mine are summarized in Table 1, and the parameters utilized in the geochemical model are listed in Table 2.

A comparison of predicted versus observed spoil groundwater chemistry is illustrated in Figure 4 and summarized in Table 3. As at the Battle River

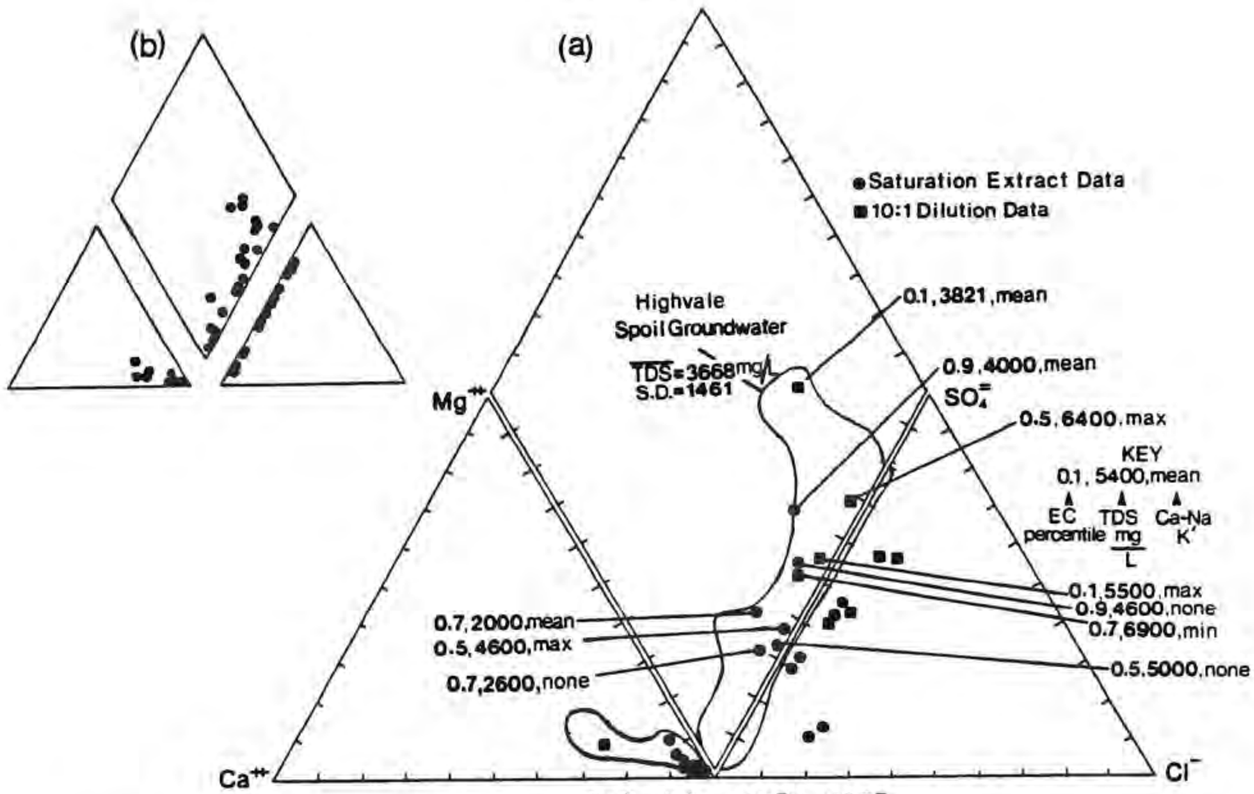

Figure 4. (a) Piper trilinear diagram of calculated spoil groundwater chemistry at Highvale Mine
(b) Observed composition of spoil groundwater samples from Highvale Mine

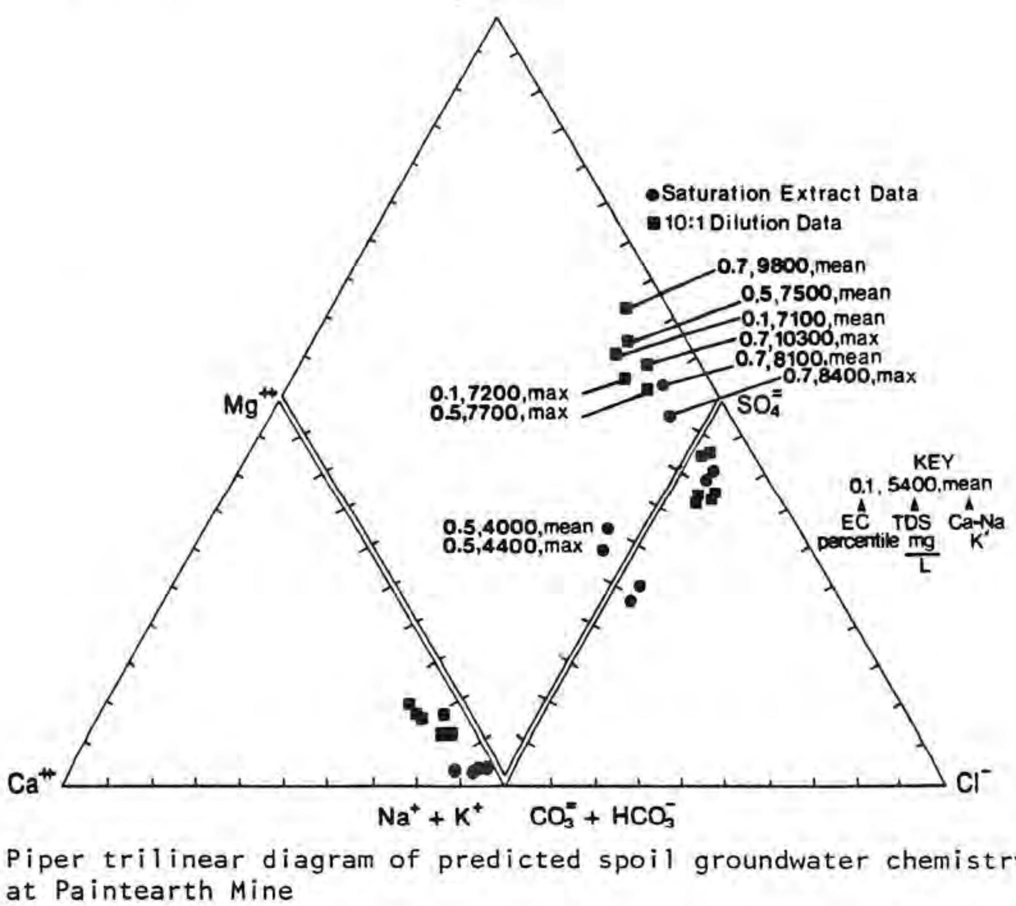

Figure 5. Piper trilinear diagram of predicted spoil groundwater chemistry at Paintearth Mine

mining area the ion exchange characteristics of the overburden materials were based on pre-mining groundwater samples, however, very little data from undisturbed sites are available close to the instrumented spoil area at Pit 01 of the mine. Consequently, the quantification of overburden ion exchange characteristics at this site may not be a reliable basis for estimating spoil ion exchange/properties.

The predicted groundwater chemistry at Highvale Mine differs from those at Battle River area mines in that saturation extract-based predictions correspond to the minimum and mean of observed chemistry (as opposed to minimum and maximum), and 10:1 dilution-based predictions correspond to the upper range of observed spoil groundwater chemistry. Predictions based on 10:1 dilution data groups from 0.1, 0.5 and 0.7 EC Percentiles, with maximum or minimum K' values, yielded groundwater TDS concentrations of 5500 to 6950 mg/L, compared to the observed salinity of spoil groundwater which has a mean TDS concentration of 3668 mg/L, a standard deviation of 1461, and a maximum of 6855 mg/L. The salinity predicted from saturation extract data ranges from 2000 mg/L to 5000 mg/L, and is in reasonable agreement with the minimum (1220 mg/L) to mean (3668 mg/L) observed TDS concentrations, as well as the observed spoil groundwater composition. The data groups corresponding to 0.5, 0.7, and 0.9 EC percentiles again provided the best match, and mean and maximum K' values, or no consideration at all of ion exchange, provided the best match for the observed spoil groundwater chemistry. The agreement obtained without considering ion exchange may reflect (1) low ion exchange capacities of the overburden materials, or (2) poor representation of local ion exchange properties from regional overburden data. Further investigation of the role of ion exchange as a predictive parameter is required to resolve this apparent inconsistency.

Paintearth Mine

Paintearth Mine in the Battle River mining area was opened in late 1981. In the area first mined the glacial drift cover was very thin (on the order of 30 cm) and salvaged as subsoil. Consequently, the spoil at Paintearth Mine is made up almost entirely of bedrock from the Horseshoe Canyon Formation.

The predicted groundwater chemistry for spoil at Paintearth Mine is illustrated in Figure 5 and summarized in Table 3. Since wells in the spoil at Paintearth Mine are still dry, the predicted groundwater chemistry is truly a prediction, an evaluation of which will be undertaken when the spoil resaturates. The essential feature of spoil groundwater at Paintearth Mine, based on the predictive model, are expected to be: TDS range from 4000 to 10000 mg/L; mean TDS approximately 7100 to 7500 mg/L; composition $Na^+ - SO_4^=$, with $Ca^{2+} + Mg^+$ comprising as much as 30% of the cation fraction, and HCO_3^- generally as much as 20% of the anion fraction.

Sulfate Reservoir

An important feature of the geochemical model is its ability to quantify the amount of undissolved sulfate remaining in the spoil after one pore-volume of flushing. This sulfate, probably in the form of gypsum, will be available for re-dissolution as fresh water recharges the spoil, thereby acting to maintain relatively high salinity groundwater in the spoil for an extended period of time.

The amount of undissolved sulfate in the spoil (the sulfate 'reservoir') for Diplomat and Vesta mines is summarized in Table 4. At Highvale Mine, all of the predicted water chemistry examples, from both 10:1 dilution and saturation extract data, showed no remaining sulfate. At Paintearth Mine, only one sample out of 10 indicated undissolved sulfate, and from that sample (10:1 dilution, EC 0.7 group, mean K' value) only 2.8% of the original sulfate remained undissolved.

Data from Diplomat and Vesta Mine, on the other hand, indicate that a significant amount of sulfate can remain undissolved. At Vesta Mine, as much as 76% of the original sulfate remained undissolved, with saturation extract and 10:1 dilution tests yielding comparable results. At Diplomat Mine, as much as 94 percent of the original sulfate remains in the solid phase, with the 10:1 dilution data better quantifying the total available sulfate and therefore probably providing a better estimate of the sulfate reservoir. This likely results from the solubility limits of gypsum reached during the saturation extract test, thereby underestimating the total soluble sulfate in the sample.

Table 4. Sulfate Reservoir in Spoil After One Pore-Volume Leaching

Mine	Method[1]	Sample Group EC Percentile	*K'	Moles/Kg $SO_4^=$ Reserve	%Original $SO_4^=$ Reserve
Vesta	SE	0.5	mean	0.	0
		0.5	max	0.	0
		0.7	mean	0.013	76
		0.7	max	0.008	46
		0.9	max	0.009	39
	10:1	0.1	mean	0.	0
		0.1	max	0.	0
		0.5	mean	0.009	63
		0.5	max	0.0035	25
		0.9	max	0.0194	57
Diplomat	SE	0.5	mean,max	0.	0
		0.7	mean	0.	0
		0.7	max,max	0.	0
		0.7	mean,max	0.011	82.5
		0.9	mean,max	0.035	90.4
	10:1	0.1	mean,max	0.0016	25.5
		0.5	min,max	0.029	93.7
		0.5	mean,max	0.028	89.8
		0.9	mean,max	0.070	93.7
Highvale	SE,10:1	all classes		0.	0

[1] SE = saturation extract; 10:1 = 10:1 Dilution test

* single value refers to Ca-Na K°; two values are Ca-Na, Mg-Na K° values, respectively

From these results it is clear that the presence of high-salinity, calcareous till in spoil material can have a significant impact on the gypsum saturation characteristics of the spoil groundwater, and on the buildup of a sulfate reservoir in the spoil material. These results suggest that at Highvale and Paintearth Mines spoil groundwater salinity should decrease significantly after the first pore-volume of spoil resaturation, whereas at Diplomat and Vesta Mine the salinity of spoil groundwater will remain high during flushing by additional pore-volumes.

Effects of Coal Ash Disposal

The disposal of coal ash in pits at surface coal mines has the potential to significantly alter the chemistry of the spoil groundwater. To evaluate the magnitude of this alteration, the salt-yielding characteristics of fly ash and bottom ash from the Battle River Generating Station (Alberta Power Ltd.) in the Battle River mining area were determined from a 40:1 (water: sediment) leaching experiment. A procedure very similar to the one described above for predicting post-mining groundwater chemistry was used to evaluate the interaction between ash and spoil groundwater. The geochemical model PHREEQE was used to numerically dissolve the soluble constituents of fly ash and bottom ash in spoil groundwater. The modeling procedure was calibrated against two sets of laboratory experiments (one at atmospheric P_{CO_2}, the other at 0.25 atm P_{CO_2}), then used to predict the results of interaction of spoil groundwater and ash under in-pit disposal conditions.

The results of ash disposal on groundwater from Diplomat and Vesta Mines are illustrated in Figures 6 and 7. Significant increases in almost all species are expected, with increases in total dissolved solids from 690 to 4355 mg/L for bottom ash and fly ash respectively, at Vesta Mine, and from 1877 to 5408 mg/L for bottom ash and fly ash respectively, at Diplomat Mine. At both mines there is little change in spoil groundwater composition due to bottom ash disposal, but a significant increase in the percentage of sodium as a result of fly ash disposal, as illustrated in Figure 6.

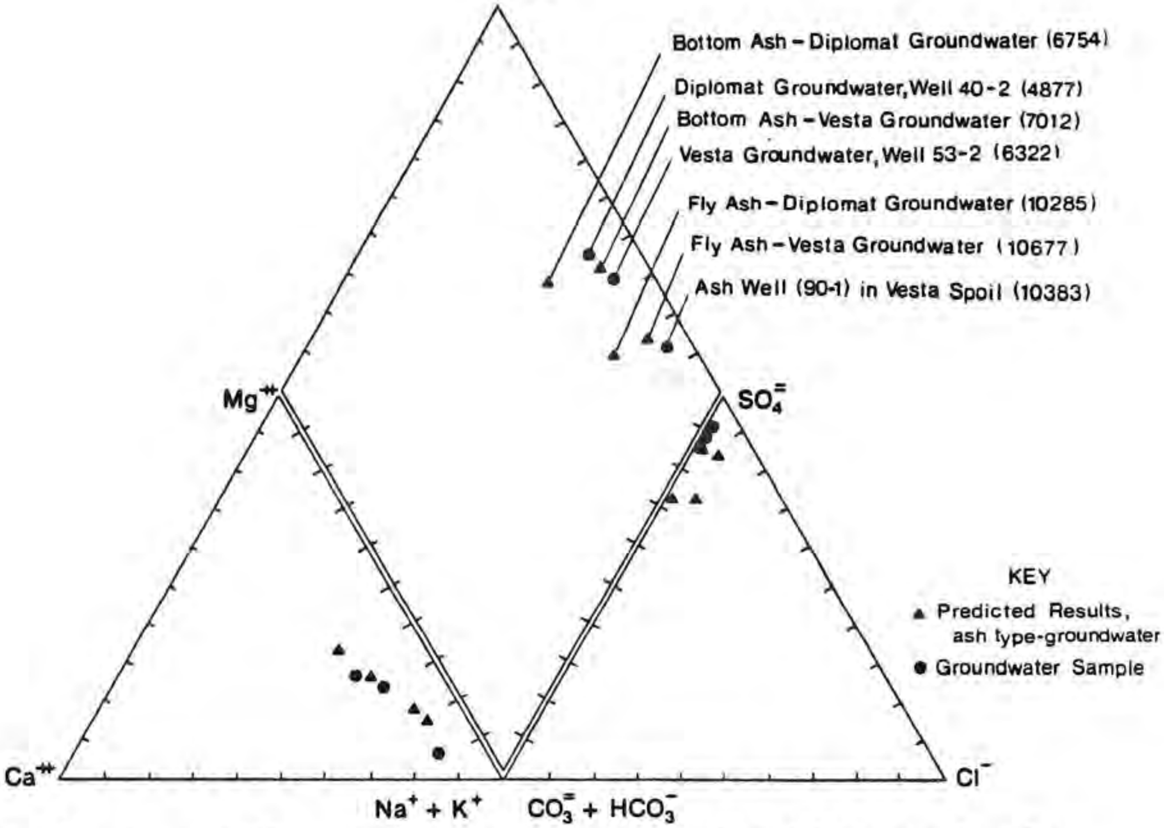

Figure 6. Piper trilinear diagram of geochemical modeling results for combinations of coal ash and spoil groundwater. Groundwater compositions are included for Vesta spoil groundwater, Diplomat spoil groundwater and well in an ash disposal area of Vesta Mine. Included in brackets are TDS values in mg/L.

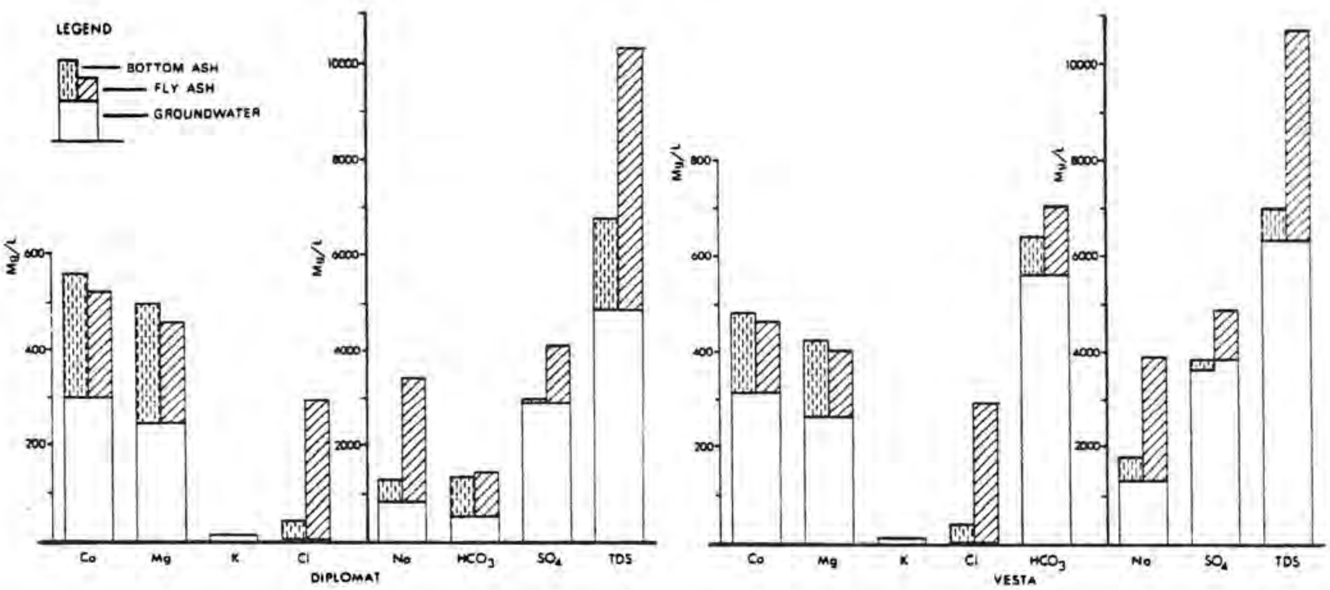

Figure 7. Graphical representation of the predicted effects of fly and bottom ash disposal on spoil groundwater chemistry at Diplomat and Vesta Mines.

A sample of groundwater has been collected from a well (90-1) in an ash disposal site at Vesta Mine. As shown in Figure 6, the predicted composition and salinity (10,677 m/L) based on Vesta spoil groundwater - fly ash in very good agreement with the actual composition and salinity of groundwater (10,383 mg/L) at the disposal site.

CONCLUSIONS

Pre-mining overburden characteristics can be used to successfully predict post-mining spoil groundwater chemistry. Leach test extracts, including both 10:1 dilution and saturated pastes are suitable for characterizing overburden salt-yielding characteristics, but in calcareous materials the 10:1 dilution provides a better estimate of total salt yield.

Overburden salt yielding characteristics used in conjunction with the geochemical model PHREEQE provide a reasonable estimate of the range of spoil groundwater composition and salinities that have been observed at several mine sites. Ion exchange, based on a modified selectivity coefficient determined from pre-mining groundwater samples, is an important process in most spoil groundwater settings, but further study is required to fully evaluate the role of ion exchange and to examine other techniques for quantifying this parameter.

For predicting post-mining groundwater chemistry, data groups corresponding to the 0.5 and 0.7 EC percentiles from saturation extract tests, and 0.1 and 0.5 EC percentiles from 10:1 dilution tests, provided the best match with observed spoil groundwater chemistry. Also, in most cases, mean and maximum K' values were used to provide good agreement with observed spoil groundwater chemistry.

In spoil where saline calcareous drift is a significant component, a large percentage of the available sulfate remains undissolved after one pore-volume of flushing, allowing for significant salinity to develop in subsequent pore-volumes of spoil groundwater.

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RECLAMATION IN MOUNTAINS, FOOTHILLS AND PLAINS: **DOING IT RIGHT!**

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