Prediction of Source Term Leachate Quality from Waste Rock Dumps: A Case Study from an Iron Ore Deposit in Northern Sweden

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Abstract

The prediction of source term water quality from mine waste disposal facilities is an important aspect of the design and management of mining operations. Predictive numerical calculations have been completed for the assessment of long-term leachate chemistry emanating from a proposed Waste Rock Dump (WRD) at an iron ore deposit in Northern Sweden. The prediction required the generation of source term water quality for the WRD in terms of solute concentrations and loading, in addition to assessing the effects on water quality in the receiving watercourse adjacent to the facility. A source term was developed from the results of laboratory static and kinetic testwork carried out on drillcore samples of representative waste rock lithologies. Based on static testwork results, the WRD material consists of two broad material types: (i) Potentially Acid Forming (PAF) skarn with a sulfur content >1%, which makes up 34.3Mt of the 124Mt estimated waste, and (ii) Non-Acid Forming (NAF) material types with a sulfur content <1%, making up the remaining waste. Mass balanced Humidity Cell Test (HCT) and Net Acid Generation (NAG) test results were used to develop source terms for WRD scenarios during Life of Mine (LOM) and post-closure. Model scenarios included: (i) segregated and unsegregated waste; (ii) spring and average snow melt conditions; and (iii) the application of standard soil and qualified covers post-closure. Modelling results demonstrated that loading of metals from the WRD was greatest during spring for the LOM scenarios; when seepage through the WRD is greatest and the material is uncovered. However, due to river flow being highest during the spring months, a dilution factor is experienced and predicted metal concentrations in the adjacent watercourse are generally lower than for average flow conditions. In all cases, segregation of high sulfur material was shown to give the best results in terms of elemental load release and predicted elemental concentrations in the adjacent river.

Key words: Water Quality, Waste Rock Dump, Source Term Predictions

Introduction

Acid Rock Drainage and Metal Leaching (ARDML) from waste rock at mine sites can be a major environmental liability that greatly complicates and adds to the expense of site closure. There are strong economic and environmental arguments for improving the accuracy of predicting if and when a Waste Rock Dump (WRD) will turn acid. Quantitative model parameters need to be obtained from a systematic laboratory study of the waste material in question. To allow a meaningful prediction of long-term leachate quality to be made, a detailed knowledge and understanding of site specific hydrologic, climatic and geological conditions is required.

Numerical modelling and assessment of long-term leachate chemistry was carried out for a proposed WRD at an iron ore deposit in Northern Sweden. The main objective of the modelling exercise was to predict source term water quality in terms of solute concentrations and loading emanating from the WRD into the adjacent watercourse during Life of Mine (LOM) and following closure.

Methodology

Sampling

Leapfrog 3D visualisation software package (Version 2.2.1.44) was used to identify spatially and lithologically representative samples of waste rock for geochemical characterisation testing. A total of thirty three waste rock samples from drill core were collected and sent for analysis at a commercial accredited laboratory. Details of the sampled lithologies are shown in Table 1.

Table 1 *Breakdown of sampled lithologies*

Rock Type	Lithology	Number of samples
Skarn	Actinolite skarn	2
Skarn	Clinopyroxene actinolite	3
Skarn	Clinopyroxene skarn	6
Skarn	Clinopyroxene-Actinolite	1
Skarn	Serpentine skarn	2
Skarn	Skarn (Tactite)	2
Skarn	Tremolite skarn	1
Granite	Granite	3
Volcanic	Intermediate Volcanic Rock	1
Volcanic	Mafic Volcanic Rock	3
Marble	Marble	3
Other Meta/Intrusives	Amphibolite	1
Other Meta/Intrusives	Greenstone	1
Other Meta/Intrusives	Monzodiorite	2
Other Meta/Intrusives	Quartz Phyllite	2

Laboratory Testwork

Static and kinetic laboratory tests were undertaken, in addition to a mineralogical study, on the samples in order to determine the elemental and mineralogical composition of the waste rock, and to understand the leaching behaviour of each rock type. The static tests completed were: multi-element analysis using aqua regia digest following by ICP analysis; Acid Base Accounting (ABA); Net Acid Generation (NAG) testing with leachate analysis; short term leach test (in accordance with BS EN 12457-3 [BSI 2002] at a 2:1 and 8:1 liquid to solid ratio) and mineralogical analysis.

The results of the static test showed that the majority of samples fall into Non-Acid Forming (NAF) category; having a sulfide sulfur content less than 0.5% or a Neutralising Potential Ratio (NPR) greater than three and a NAG pH less than 4.5. Based on the ABA results, five skarn samples are classified as Potentially Acid Forming (PAF) and the remaining samples were classified as NAF or uncertain.

Based on the static results, the WRD material is defined as consisting of two main material types:

(i) PAF skarn with a sulfur content >1%, which makes up 34.3Mt of the 124Mt estimated waste (i.e., 28%); and

(ii) NAF material types (granite, marble, volcanics) with a sulfur content <1%, make up the remaining 72% of waste (approximately 89.7Mt).

Subsequently kinetic Humidity Cell Tests (HCT) in accordance with ASTM D5744-96, were run on two NAF skarn samples, a NAF marble sample and three PAF skarn samples for a period of between 40 – 60 weeks. Weekly leachate analysis was carried out by ICP-OES and ion chromatography.

Conceptual Model

Conceptual geochemical models were developed from a review of background and site-specific data. Conceptual models were developed for both a LOM scenario and a post-closure scenario and are illustrated in *Figure 1*. Mass balanced HCT and NAG test results were used to develop source terms for the following model scenarios:

(i) Segregated (PAF and NAF cells) and unsegregated (blended PAF and NAF) waste;

(ii) Spring and average snow melt conditions; and

(iii) The application of standard soil and qualified covers post-closure (reducing infiltration).

Source term results for LOM average, LOM spring and closure options using different qualified covers have been combined with average (0.7m^3/s) and high spring (7.29m^3/s) river flow conditions in the adjacent watercourse to determine the impact of seepage on receiving surface water.

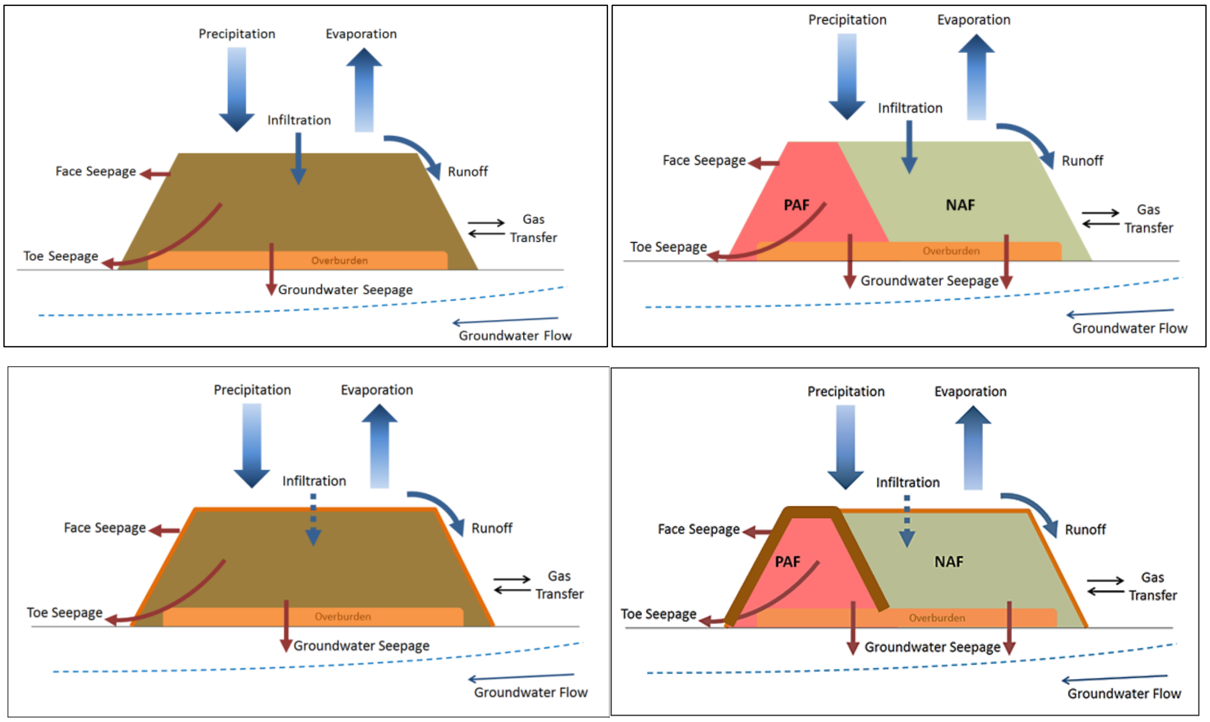

Figure 1 *Conceptual models for blended (left) and segregated (right) WRD during LOM (top) and post-closure (bottom)*

A scaling factor was applied to the laboratory data in order to account for the differences in reaction rates and liquid to solid ratios between the laboratory test and field conditions. The chemical and physical scaling factors applied in this paper are based on methods presented by Kempton (2012), whereby up-scaling factors are applied to the prediction of field scale seepage from laboratory tests. A summary of the scaling factors applied are presented in Table 1 below. Climate monitoring data for the site was utilised to provide estimates of evaporation and precipitation rates. Surface water quality for source term mixing was obtained from river water sampling previously completed by SRK. The rainwater used in the models is generic Northern Europe rainwater (USGS 1997). Water chemistry predictions were made using the geochemical modelling code PHREEQC, version 3.3.5-10806 (Parkhurst & Appelo 1999) together with an in house modified version of the MINTEQ.v4 database.

Table 2 *Modelling parameters summary*

Parameter		**Value Applied**		
		LOM Average	**LOM Spring**	**Closure**
	Infiltration (mm/yr)	265	1694	98
	Seepage (m^3/day)	1278	5951	471
	Oxygen ingression	Based on ANSTO model^{*1}		
Scaling factors	NAG	0.001% for all scenarios		
	HCT	No distinct factor used		
Chemical scaling	Temperature	26% for all scenarios		
	O_2^{*2}	50% of atmospheric for all scenarios		
Physical scaling	Proporation fines	20% for all scenarios		
	Proporation fines flushed	50% for all scenarios		

^{*1} *Convective airflow minimised and O_2 mass transport by diffusion*

^{*2} *Average concentration over penetration depth*

Results and Discussion

The predicted source term water quality output results from each iteration of the model scenarios (using NAG and HCT data) are shown in Table 3. Source term results for the LOM average, LOM spring and the closure scenarios have been assessed against average (0.7 m^3/s) and high spring flow (7.29m^3/s) conditions in the river adjacent to the WRD in order to predict river water quality as shown in Table 4.

Generally the predicted concentrations of metals in the source term waters are found to be greater when using the NAG tests results. Modelling results indicates that loading of metals from the WRD is the greatest during spring for the LOM scenarios; when seepage through the WRD is greatest (at 5951m^3/day) and it is uncovered (Table 3). However, due to river-flow being higher during the spring months a dilution factor is experienced and predicted metal concentrations in the adjacent watercourse are therefore lower than for average flow conditions (Table 4).

Post closure loading of metals from the WRD is significantly lower than during the LOM, this is due to the lowering of seepage from the dump (to 471m^3/day) through the application of a qualified cover. By reducing the global oxidation rate (GOR) into the dump through the application of a cover the loadings subsequently decrease due to infiltration and oxidation being limited. By decreasing the oxidation rate within the dump the mobilisation of elements is also decreased resulting in an improvement in the river water quality. Scenarios in which NAG data was run generally produced higher concentrations/poorer water quality.

In all cases, segregation of high sulfur (PAF) material is shown to give the best results in terms of elemental load release and predicted elemental concentrations in the adjacent river. None of the scenarios predicted the generation of acidic conditions due to a combination of segregation and buffering from silicate phases. The seepage pH was near neutral, ranging from 7.45 - 7.64 in all model scenarios.

Table 3 *Predicted chemical loadings from the WRD based on NAG/HCT test results.*

		Predicted chemistry based on NAG test results						Predicted chemistry based on HCT test results					
		Segregated WRD			Blended WRD			Segregated WRD			Blended WRD		
		LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average
Seepage m^3/day		*1278.4*	*5950.9*	*470.7*	*1278.4*	*5950.9*	*470.7*	*1278.4*	*5950.9*	*470.7*	*1278.4*	*5950.9*	*470.7*
Cl	g/day	1250	5730	461	1260	5840	460	264000	1310000	263000	397000	294000	350000
F	g/day							2300	3750	2130	1990	1450	1810
SO4	g/day	1040000	3750000	989000	1030000	1040000	1010000	669000	2030000	666000	759000	552000	603000
N as NO_3	g/day	85.9	395	31.3	86.5	404	31.3	255	669	197	230	511	153
Ca	g/day	114000	738000	67800	174000	345000	137000	122000	531000	109000	141000	291000	115000
K	g/day	64000	64600	80800	34900	35600	34600	101000	256000	101000	105000	76800	98500
Mg	g/day	155000	538000	101000	137000	279000	121000	363000	1210000	325000	422000	423000	344000
Na	g/day	279000	401000	344000	171000	175000	170000	98500	106000	97700	77000	58700	71900
Al	g/day	0.03	0.128	0.0106	0.0281	0.137	0.0102	0.0298	0.135	0.0118	0.0294	0.134	0.0113
Fe	g/day	0.503	3.19	0.221	0.655	2.32	0.309	0.568	2.7	0.294	0.615	2.51	0.312
Ag	g/day	1.95	10.5	0.919	2.57	6.29	1.28	6.75	15.9	8.15	9.42	6.2	7.26
As	g/day	0.00148	3.95	5.98	0.00168	0.00148	0.00113	0.0129	0.724	0.00544	0.0116	0.005	0.000109
Cd	g/day	1.51	3.28	6.33	1.87	0.177	1.58	21.5	133	18.4	43.6	4.31	0.598
Co	g/day	543	237	560	584	152	508	21.3	34.3	18.4	18.9	4.9	0.753
Cr	g/day	0.000662	1.67	0.101	0.000912	0.0000585	0.000493	0.0000874	1.41	0.0000399	0.000252	0.0000255	0.00000123
Cu	g/day	23	78	9.37	19	6.82	7.19	0.54	40.7	0.168	1.22	0.244	0.00762
Hg	g/day	0.903	2.67	4.29	0.707	0.407	0.281	1.47	2.44	1.5	1.5	0.619	1.09
Mn	g/day	1140	912	1030	1680	397	1480	650	1560	579	682	165	24.8
Mo	g/day	1380	1270	2180	731	718	599	875	729	770	614	427	67.5
Ni	g/day	28.9	25.7	54.2	32.1	4.77	23.3	16.3	51	10.8	16.1	2.25	0.184
Pb	g/day	0.035	11.8	2.64	0.0304	0.00248	0.0151	0.00374	3.27	0.00118	0.00298	0.00034	0.0000117
Sb	g/day	18.5	16.7	23.4	9.97	10.1	9.9	27.9	38.2	27.8	23	16.8	20.4
Se	g/day	0.974	11.8	19.9	1.55	1.22	0.787	1.89	10.5	0.655	1.35	0.605	0.0137
U	g/day	8.05	13.3	9.87	5.33	5.37	5.28	42.1	78.8	41.6	38.5	28	28.2
Zn	g/day	113	69.1	165	109	12	81.1	6.03	48.8	3.82	6.38	0.673	0.0547

***Table 3** Predicted water quality in river adjacent to WRD for average and spring flow conditions*

			Predicted chemistry based on NAG test results						Predicted chemistry based on HCT test results					
			Segregated WRD			Blended WRD			Segregated WRD			Blended WRD		
		SS30-Median	LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average	LOM Average	LOM Spring	Closure Average
	Flow m^3/s	*0.7*	*0.7*	*7.29*	*0.7*	*0.7*	*7.29*	*0.7*	*0.7*	*7.29*	*0.7*	*0.7*	*7.29*	*0.7*
Cl	mg/L	0.623	0.644	0.632	0.631	0.644	0.633	0.631	5	2.71	4.97	7.18	1.09	6.42
F	mg/L								0.038	0.00595	0.0353	0.0329	0.0023	0.0299
SO4	mg/L	1.4	18.6000	7.35	17.8	18.4	3.04	18.2	12.5	4.62	12.4	13.9	2.28	11.4
N as NO_3	mg/L	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51	1.51
Ca	mg/L	4.24	6.13	5.41	5.36	7.12	4.79	6.51	6.25	5.08	6.05	6.57	4.7	6.15
K	mg/L	0.587	1.65	0.69	1.92	1.16	0.644	1.16	2.26	0.993	2.25	2.32	0.709	2.22
Mg	mg/L	1.15	3.71	2	2.81	3.42	1.59	3.15	7.16	3.06	6.52	8.12	1.82	6.83
Na	mg/L	1.42	6.03	2.05	7.1	4.24	1.69	4.22	3.04	1.58	3.03	2.69	1.51	2.6
Al	mg/L	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4
Fe	mg/L	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
Ag	µg/L		0.0323	0.0167	0.0152	0.0424	0.00998	0.0212	0.112	0.0252	0.135	0.156	0.00985	0.12
As	µg/L	0.097	0.097	0.103	0.196	0.097	0.097	0.097	0.0972	0.0981	0.097	0.0971	0.097	0.097
Cd	µg/L	0.00435	0.0293	0.00955	0.109	0.0352	0.00463	0.0305	0.36	0.216	0.308	0.725	0.0112	0.0142
Co	µg/L	0.11	9.08	0.486	9.37	9.77	0.351	8.52	0.462	0.164	0.415	0.423	0.118	0.122
Cr	µg/L	0.228	0.228	0.231	0.23	0.228	0.228	0.228	0.228	0.23	0.228	0.228	0.228	0.228
Cu	µg/L	0.346	0.727	0.47	0.501	0.66	0.357	0.465	0.355	0.411	0.349	0.366	0.346	0.346
Hg	µg/L	0.0036	0.0185	0.00784	0.0745	0.0153	0.00425	0.00824	0.0279	0.00747	0.0284	0.0284	0.00458	0.0217
Mn	µg/L	21.4	40.3	22.8	38.4	49.2	22	45.9	32.1	23.9	31	32.7	21.7	21.8
Mo	µg/L	0.262	23	2.28	36.3	12.3	1.4	10.2	14.7	1.42	13	10.4	0.94	1.38
Ni	µg/L	0.157	0.634	0.197	1.05	0.687	0.164	0.542	0.426	0.237	0.334	0.423	0.16	0.16
Pb	µg/L	0.0342	0.0348	0.0529	0.0778	0.0347	0.0342	0.0344	0.0343	0.0394	0.0342	0.0342	0.0342	0.0342
Sb	µg/L	0.0116	0.317	0.0382	0.399	0.176	0.0276	0.175	0.472	0.0722	0.47	0.392	0.0382	0.349
Se	µg/L		0.0161	0.0187	0.33	0.0257	0.00194	0.013	0.0313	0.0167	0.0108	0.0223	0.00096	0.000226
U	µg/L	0.023	0.156	0.044	0.186	0.111	0.0315	0.11	0.719	0.148	0.711	0.66	0.0674	0.488
Zn	µg/L	1.26	3.13	1.37	3.98	3.06	1.28	2.6	1.36	1.34	1.32	1.37	1.26	1.26

Conclusions

A numerical predictive exercise has been reported for the assessment of long-term leachate chemistry on a proposed WRD at an iron ore deposit in Northern Sweden. The prediction required the generation of source term water quality in terms of solute concentrations and loading emanating from the WRD (for segregated and unsegregated waste rock cases) and the mixing of this in the adjacent receiving watercourse both for LOM and closure scenarios at average and high spring flow conditions.

Predicted metal concentrations in the source term waters were higher when NAG test results were used to generate source term chemistry. Predictive calculations indicate that loading of metals from the WRD is the greatest during spring LOM scenarios; when seepage through the dump is greatest and the dump is uncovered. However, predicted metal concentrations in the adjacent watercourse are lower for spring high flow than average flow conditions due to dilution caused by significantly higher river flow volumes. Post closure loading of metals from the WRD is significantly lower than during the LOM, due to the application of a qualified cover reducing infiltration and seepage.

In all cases, segregation of PAF material is shown to give the best results in terms of elemental load release and predicted elemental concentrations in the adjacent river. The application of a qualified cover over the PAF material post-closure saw a reduction in oxidation rates and a further decrease in source term metal concentrations.

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