

# Source Assessment to Support Closure Designs for the Western and Central Development Areas at a Site in Central Laos

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## Abstract

SRK Consulting (Australasia) Australia Pty Ltd (SRK) are currently assisting with the development of closure plans for the Western and Central Development Areas at a site in Central Laos. These areas include more than 40 pits, some backfilled, and 13 waste rock dumps. To support closure planning, it is important to identify which pits and dumps represent significant contaminant sources, and to understand how effectively contaminant release can be mitigated as part of the closure design.

Available information for the site included drill hole data, geological block models, current topographic surfaces, future pit and dump designs, outcomes from geochemical characterisation studies, surface and groundwater water quality monitoring data.

Conceptual models of the distribution of reactive materials and contaminant sources within key pits and dumps were developed. Post closure, the most significant ongoing sources of solute production are expected to be related to oxidising sulfide minerals present within unsaturated materials in:

- Above ground dumps
- Pit backfill located above the long term water table and
- Pit walls that remain exposed after closure, i.e. are not covered by backfill, or remain above the long
- term pit lake levels.

Field scale solute production rates (inferred from laboratory column test results) were combined with water flows to calculate water chemistry at source and downstream following mixing with other water sources. A companion paper describes development of a site water balance, including representation of surface and groundwater flows at the site.

The water quality calculations were used to examine the range of possible impacted water chemistries for (i) base case flows and solute loadings – to reflect the condition of the site prior to implementation of active closure measures, and (ii) post closure design conditions – to examine the effect of closure measures, such as emplacement of low infiltration covers on dumps.

Using the site wide water and solute load balance approach it was possible identify the optimal closure measures in terms of mitigation of water quality impacts to downstream receptors (drinking water resources).

**Keywords:** geochemistry, water quality, sulfide oxidation, acid mine drainage

## Introduction

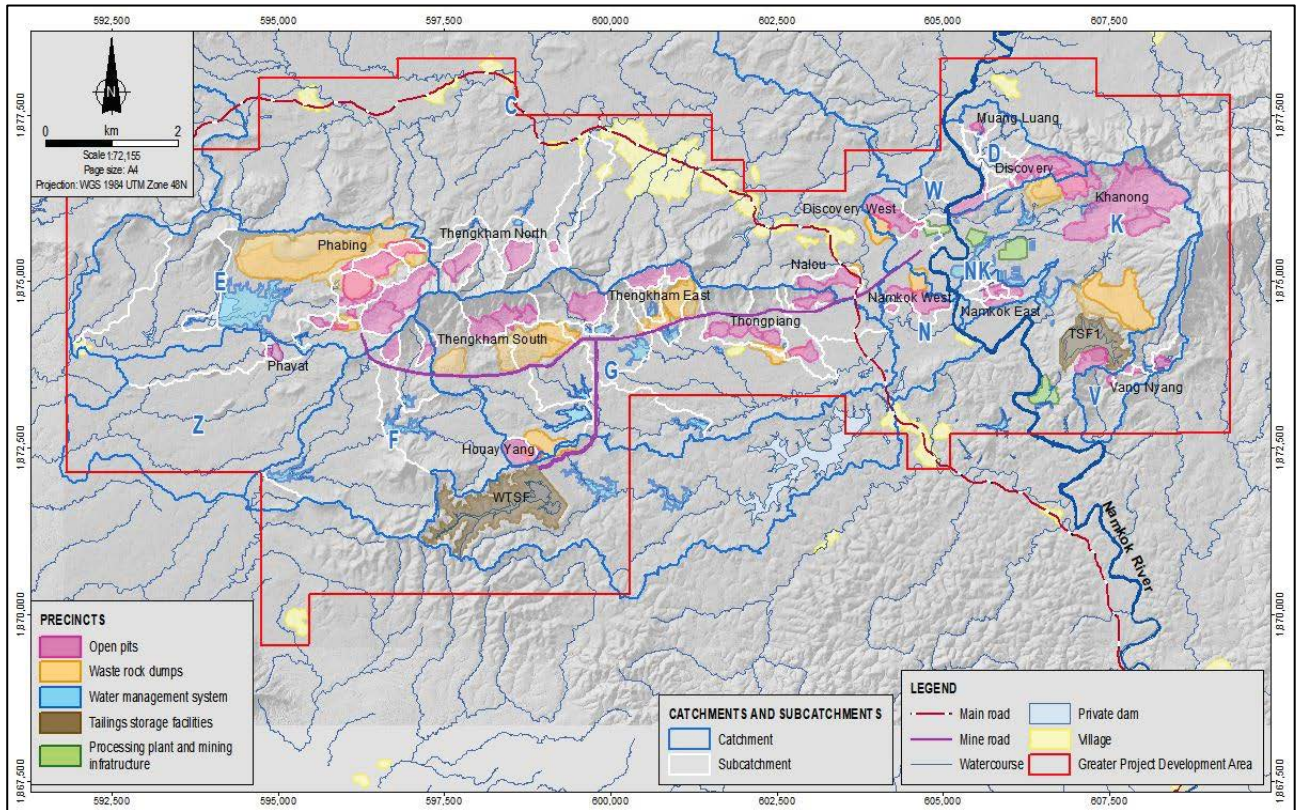
The subject mine (the site) is an open cut gold and copper mining operation located in central Laos. Mining operations comprise several gold and copper open pit operations, with the gold operations currently in care and maintenance. Figure 1 shows the site layout comprising open pits, waste rock dumps, and water management structures. Mining intersected sulfidic lithologies, and acid mine drainage (AMD) is occurring at various locations across the site. AMD is associated with oxidising pit wall rocks, and potentially acid forming (PAF) rock contained in some of the waste rock dumps.

For the purposes of closure planning, the operations have been separated into three distinct areas:

- Western and Central Development Areas
- Khanong mining area in the east
- Two tailings storage facilities (TSF1 and WTFSF)

The current paper describes a geochemical assessment conducted to quantify the potential for dumps and pits to represent ongoing sources of contaminants, post closure, for the Western and Central Development Areas. These areas include more than 40 pits and 13 waste rock dumps.

The assessment formed part of a multi disciplinary approach to support development of overall closure designs (the overall approach is described in a companion paper, Chapman et al. 2018).



**Figure 1: General layout of the subject mine site.**

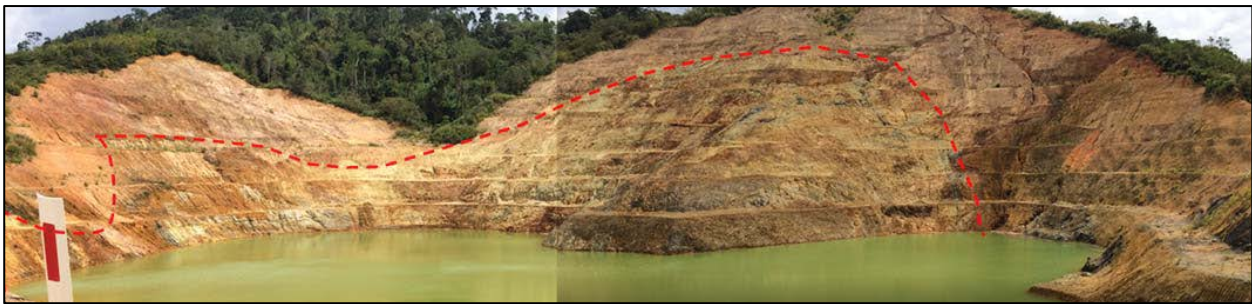
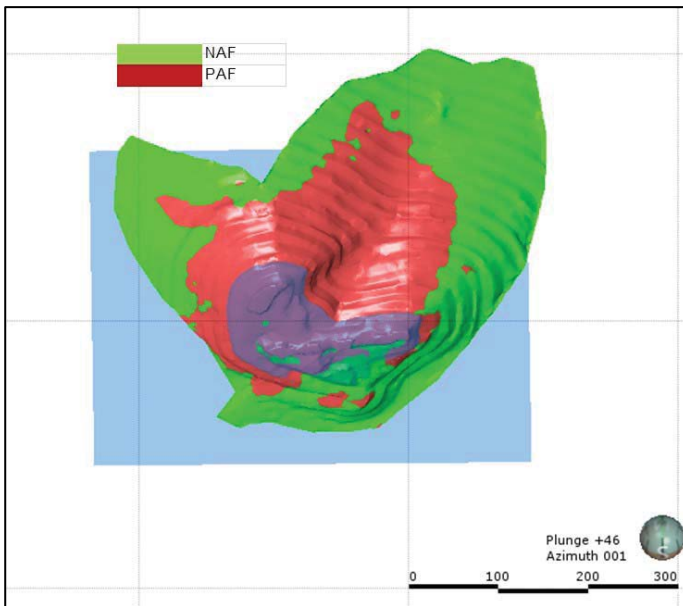
## Conceptual Models

Solute production at the site has been conceptualised based on the distribution of sulfidic materials within unsaturated materials exposed by mining activities. Air and water ingress to such materials results in sulfide oxidation and associated solute production. Post closure, the main sources of ongoing solute production are expected to be sulfidic materials present in:

- Above ground dumps
- Backfill placed in pits that will remain above the long term water table and
- Pit walls that remain exposed after closure (i.e. are not sufficiently covered by backfill, or remain above the long term pit lake levels).

The operation manages mineralised waste rock according to a sulfur cut off threshold (independent of acid neutralising capacity, ANC) to infer the acid generation potential. Material with total sulfur content above the threshold is classed as PAF whilst material with a sulfur content below this cut off is classed as non acid forming (NAF). Typically, the sulfur threshold value used at site was 0.3% total sulfur.

Geological block models, pitshells, and mine scheduling information were used to estimate quantities, and distributions, of PAF and NAF materials within dumps and on pit walls. As an example, Figure 2 shows a 'map' of the distribution of NAF (green) and PAF (red) on the walls of one of the Thengkhamb pits. The PAF/NAF maps generated from the block models were found to be in agreement with field observations (as shown in the photographic image below the figure).



**Figure 2: Distribution of PAF and NAF-classed materials on pit walls, Thengkham South D**

## Source Term Development

### General Principles

Solute source terms were developed using a combination of:

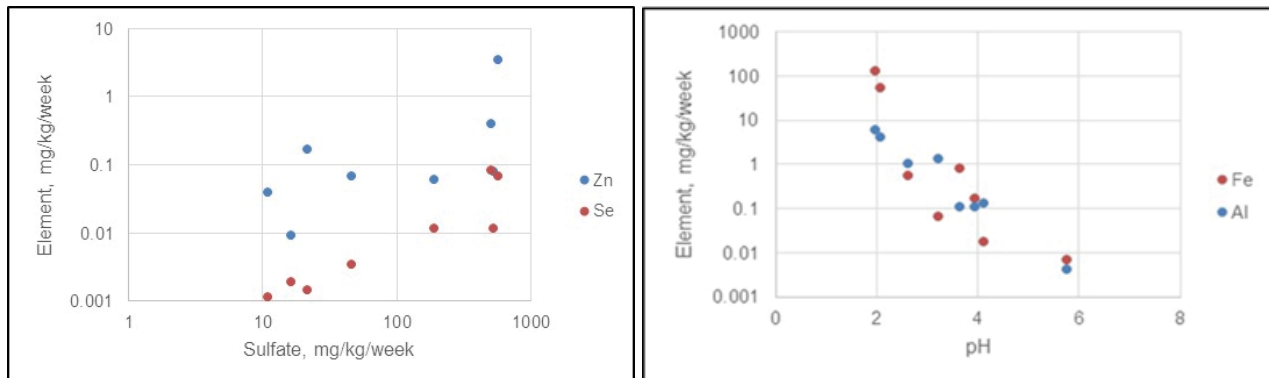
- Laboratory data – the site's geochemical database included data from small scale free draining column tests. Trends in the datasets were used to determine solute production rates and controls. Laboratory derived rates were extrapolated or 'scaled' to field conditions as discussed below.
- Site based observations and water quality monitoring results. Seep survey and water quality monitoring results proximal to AMD sources provided the range of solute concentrations that occur at site.

### Solute Production Rates and Controls

The site's geochemical database included data from eight small scale free draining columns conducted on waste rock. Average long term solute production rates were calculated using leachate chemistries observed from Week 40 to 52 of testing (i.e. towards the end of the tests). Trends in the dataset were used to infer solute production rates and controls as follows:

- Sulfate release rates did not correlate well with sulfur content - possibly a reflection of complex sulfide mineralogy within the samples. For example, mineralogical descriptions suggest that samples contain combinations of pyrite ( $\text{FeS}_2$ ) and chalcocite ( $\text{Cu}_2\text{S}$ ) which would be expected to oxidise at different rates.
- Leachate pH during testing was largely consistent with sample classification; seven of the eight samples were classed as PAF, and leachates were acidic (average pH ranging between 2 and 4). The one NAF sample tested gave an average pH of 6.
- Ca and Mg release rates were relatively high from the NAF sample, consistent with neutralisation by Ca and Mg bearing carbonate minerals. Mn release was concurrently high, possibly indicating that carbonate minerals may represent a source of Mn in rocks. This inference was supported by site observation – relatively high dissolved Mn (greater than 10 mg/L) concentrations occur in neutral seepage from the Thengkham South waste dump, and in neutral pit lake water in the Namkok East area.

- Some minor and trace element release rates are positively correlated with sulfate release, e.g. Co, Cu, Ni, Se, Zn (Se and Zn are shown in Figure 3). Such correlations suggest that the elements are either (i) present in the matrix of the reacting sulfide minerals, or (ii) sourced from minerals (e.g. carbonates, silicates) reacting in response to the acidic conditions produced by sulfide oxidation.
- Some elemental releases are controlled by pH dependent mineral solubility, such as Al and Fe as shown in Figure 3 (consistent with solubility of hydroxysulfates or hydroxides).



**Figure 3: Minor and trace element release as a function of sulfate release (left) and pH (right).**

**Scaling for Application to Pits and Dumps**

At field scale, conditions differ from the controlled conditions applied during laboratory testing. Amongst other factors, sulfide oxidation rates are a function of the composition of the oxidising material, transport of reactants such as oxygen and water, and temperature. Within a full scale waste rock dump, oxidation rates will be spatially and temporally variable. To utilise the laboratory derived solute production rates to estimate long term weathering rates, a series of ‘scaling factors’ and other approximations were adopted (see Table 1). Values for the scaling factors are assigned based on a combination of theoretical considerations (e.g. surface area as a function of particle size, expected gas transport mechanism) and professional experience. Laboratory derived rates were combined with the scaling factors presented in Table 1 to generate a set of field scale solute production rates (per m2) that were applicable to NAF and PAF portions of the pit walls and dumps, see Table 2. NAF production rates were estimated on the basis of NAF classed material. PAF field scale production rates were estimated using the average of column data for samples with sulfur content greater than 0.3%.

**Table 1: Summary of base case scaling factors and approximations.**

Description	Units	Talus		Exposed wall rock		Dump/ backfill run-off		Dump/ backfill seepage	
		NAF	PAF	NAF	PAF	NAF	PAF	NAF	PAF
Surface area correction	-	0.2	0.2	0.01	0.01	0.2	0.2	0.2	0.2
Fraction flushed by rainfall/infiltration	-	0.4	0.4	0.1	0.1	0.5	0.5	0.3	0.3
Assumed thickness oxidising <sup>[1]</sup>	M	1	0.5	1	0.3	1	0.5	10	3

[1] In the full scale landform, oxygen may not be readily available in volumes where oxygen consumption rates exceed rates of oxygen supply – e.g. interior of large waste dumps, and intact rock volumes located behind pit walls. There is insufficient data to fully define gas transport processes in the context of the site landforms. For the current assessment, oxygen availability has been approximated using an assumed thickness for the actively oxidising zone. Zones are thinnest for reactive PAF materials and for intact pit walls (where low porosity and permeability would be expected to result in slow gas transport).

[2] No overt evidence of high temperatures was observed in the field (e.g. steam emanating from dump surfaces). It is considered likely that dump construction practices (i.e. PAF encapsulation) may be limiting oxidation rates and heat generation within the dumps. The illustrative calculations therefore did not include a temperature correction.

**Table 2: Field-scale production rates for selected solutes, mg/m<sup>2</sup>/month.**

Parameter	Pit walls (talus and exposed wall rock combined)		Dump run-off		Dump seepage	
	NAF	PAF	NAF	PAF	NAF	PAF
Al	0.89	170	2.7	520	16	1900
Ca	400	150	1200	460	7300	1700
Cd	0.76	3.4	2.3	10	14	37
Cu	17	12000	53	37000	320	130000
Fe	1.5	2800	4.4	8500	27	31000
Mg	330	73	990	220	5900	800
Mn	47	6.6	140	20	860	73
Ni	0.88	5	2.7	15	16	56
Pb	0.024	0.02	0.074	0.061	0.44	0.22
Sb	0.024	0.044	0.074	0.14	0.44	0.49
Se	0.24	2.7	0.74	8.2	4.4	30
SO <sub>4</sub>	2300	28000	7100	86000	42000	310000
Zn	8.2	64	25	200	150	700

## Water Quality Estimates

### Dump and Backfill Run-Off and Seepage (During Operations and Active Closure)

Water flows for the site, including dump/backfill run off and seepage, were calculated using the Closure Water Balance Model (CWBM) described in a companion paper (Luinstra et al. 2018). Due to the highly seasonal nature of rainfall in the area, calculated flows were very variable; rapid flows in the wet season, and limited or no flow during the dry season. The solute production rates described earlier were combined with the calculated flow rates to generate chemistries for dump and backfill run off, and for basal and toe seepage.

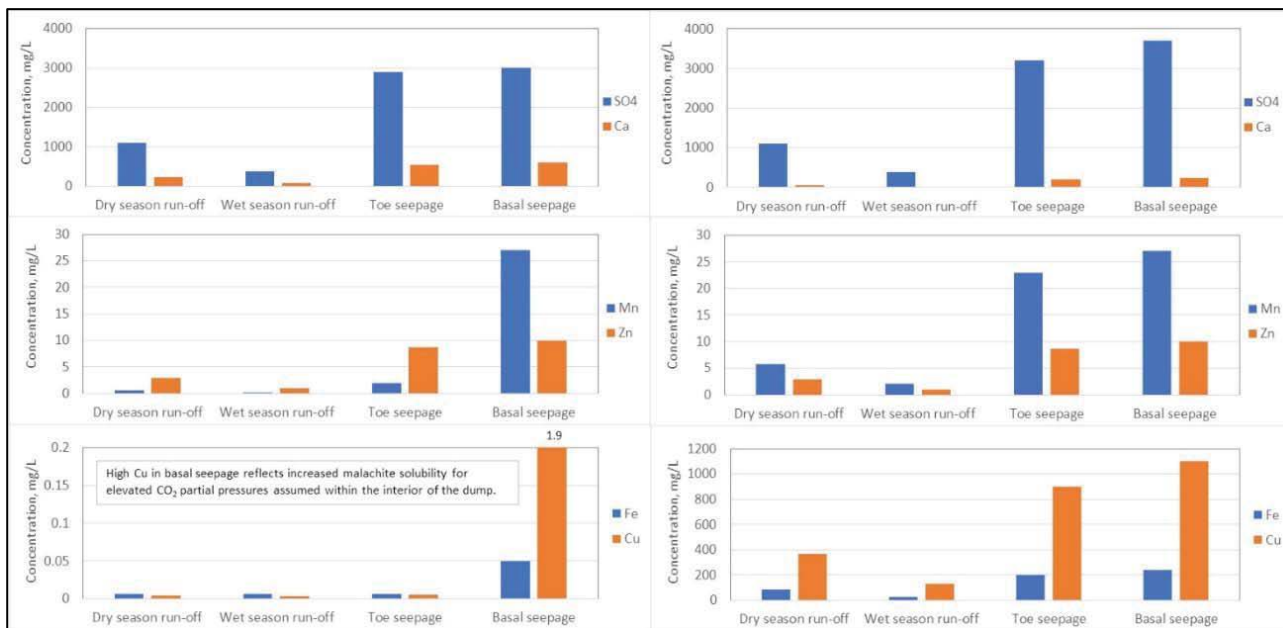
For run off, solute concentrations during dry season conditions are appreciably higher than during the wet season. In the case of basal and toe seepage, seasonal variability in surface recharge would not necessarily be observed (for example, due to water storage within the dump). For the purposes of the water quality calculations, average annual seepage quantities were generated, which were used to calculate constant monthly seepage flows.

**Table 3: Comparisons of calculated chemistry with seep survey results – selected parameters.**

Parameter	Calculated ranges		Seep survey Min – Max
	Run-off (Wet Season)	Toe Seepage	
pH	3 (ANC depleted), ~8 (neutralised)	2-5-3 (ANC depleted), ~8 (neutralised)	3 – 9.4 <sup>[1]</sup>
SO <sub>4</sub>	170-380	1,800-3,200	5 – 2,440
Ca	<20 (acid), 40-80 (neutral)	200-230 (acid), 300-550 (neutral)	3.1 – 352
Cu	30-370 (acid), ~0.004 (neutral)	200-1,000 (acid), <0.01 (neutral)	0.02 – 160
Mn	~2-7 (acid), 0.05-1 (neutral)	20-30 (acid), 1-2 (neutral)	0.012 – 28
Zn	<1-3	5-10	0.01 – 2.57

Units – mg/L, except pH

[1] The maximum pH value (9.4) corresponded to a sample from a diversion trench which may also receive flow from an agricultural area, possibly explaining the unusually alkaline pH.



(a) Neutral conditions

(b) Acidic conditions

Mineral controls: Dolomite gypsum, iron hydroxide, gibbsite, Jarosite (basal seepage only) manganite, malachite/tenorite

**Figure 4: Calculated dissolved concentrations for selected elements in run-off and seepage from the Phabing dump (during operations and active closure phases).**

Water quality was estimated for percolate contact with (and without) ANC; ANC was represented in the calculations by equilibration with dolomite. It is reasonable to expect that freshly placed material may contain ANC, and that initial run off and seepage may be pH neutral. However, ANC may not always be present, and, for PAF materials, would deplete in time. Where no ANC is available, contact water chemistry from PAF materials would be acidic. Mineral equilibrated solute concentrations were calculated using PHREEQC (Parkhurst and Appelo, 2013). In dolomite equilibrated, pH neutral solutions, dissolved concentrations of Fe, Al, Mn and Cu were calculated to be controlled by the solubility of iron hydroxide, gibbsite, manganite and malachite/tenorite, respectively. In the most saline solution chemistries – gypsum solubility placed upper bounds on dissolved SO<sub>4</sub> and Ca concentrations.

Figure 4 shows calculated dissolved concentrations for selected elements in the case of the Phabing dump, one of the largest PAF dumps at the site. The higher concentrations calculated for basal and toe seepage, compared to run off, relate to more advanced AMD from PAF materials, combined with lower volumes of contact water. Table 3 compares the ranges of calculated chemistries (for all dumps considered to represent AMD sources) with results from a seep survey conducted during 2017 (during a period of unusually high rainfall). Observed and calculated ranges compare relatively well, giving a degree of confidence that representation of solute production within the dumps is appropriate. It must however be acknowledged that both observed and calculated ranges are wide; greater confidence could be achieved with a more extensive set of observational data – for example covering wet and dry season conditions (and in particular more typical conditions than those experienced during the seep survey event).

**Dump and Backfill Run-Off and Seepage (Post-Closure)**

Following closure, once closure mitigation measures (e.g. soil covers) are in place and dump surfaces have been revegetated, run off water quality is expected to resemble natural catchment run off. Recharge to dump surfaces is expected to be reduced and other conditions may change, including:

- Infiltration rates would decrease and the fraction of material contacted by infiltrating water would be lower.
- Zones of oxidising material would be thinner, reflecting reduced oxygen supply through the cover.

Revised water balance calculations were performed to represent these changed conditions by adjusting the scaling factors to reflect field scale conditions as shown on Table 4.

**Table 4: Comparison of base case and post-closure scaling factors and approximations (dump seepage).**

Description	Units	Base Case (see Table 1)		Post-Closure	
		NAF	PAF	NAF	PAF
Surface area correction	-	0.2	0.2	unchanged	
Fraction flushed by rainfall/infiltration	-	0.3	0.3	0.05	0.05
Assumed thickness oxidising	m	10	3	5	0.5

The modelling indicated that placing covers on the dumps, to reduce both infiltration and supply of oxygen, would result in significant beneficial outcomes. Although the potential for acidic drainage (pH 3-4) remains, overall solute loadings were significantly reduced.

### Pit Lakes (Post-Closure)

Based on the net positive water balance for the site (Luinstra et al. 2018), lakes are expected to develop in the pits. To simplify the overall assessment the transient evolution of pit lake water quality during rebound has not been assessed; rather the longer term steady state conditions were estimated. The site water balance indicated that the pits will form lakes that will overflow during the wet season. Pit outflow chemistry is expected to be dominated by solute loadings from PAF material exposed on pit walls above the lake elevation.

Calculated outflow chemistry varied seasonally due to the variations in flows. During the wet season solute concentrations are diluted and lower than is the case during the dry season. Table 5 presents comparisons of calculated chemistries with routine pit lake water quality monitoring (noting that some of the pit lakes are subject to active treatment) and incidental samples obtained during the seep survey. While the concentration ranges that are calculated for wet season conditions were lower than some of the monitoring results, the calculations assume completely mixed conditions; this may not have been the case when the incidental samples were obtained as they represent shallow surface water grab samples.

Nevertheless, the calculated pit outflow chemistries lie within the (large) ranges observed in routine pit lake monitoring. As already mentioned, the routine monitoring dataset is influenced by active treatment measures in place for some of the pit lakes. Treatment increases the pH to alkaline maximum values, with a coincident reduction in dissolved concentrations of many metals.

**Table 5: Comparisons of calculated chemistry with seep survey results – selected parameters (pit lakes).**

Parameter	Calculated ranges (base case conditions; ANC depleted)		Pit Lake samples obtained during seep survey (wet season)	Water quality monitoring <sup>[1]</sup>
	Jan (Dry Season)	July (Wet Season)	Min – Max	Min – Max (25 <sup>th</sup> – 75 <sup>th</sup> percentile)
	pH	2 – 3	4 – 5	3 – 7.8
SO <sub>4</sub>	1,200 – 4,500	10 – 50	9 – 1,780	2 – 10,200 (52 – 600)
Ca	60 – 110	18 – 25	2.9 – 236	0.01 – 991 (38 – 205)
Cu	300 – 1,800	0.01 – 22	0.02 – 85	0.001 – 1,569 (0.033 – 0.85)
Mn	6 – 10	0.08 – 0.13	0.03 – 18.8	0 – 82 (0.16 – 1.81)
Zn	3 – 10	0.06 – 0.14	0.01 – 2.87	0.001 – 105 (0.02 – 0.65)

Units – mg/L, except pH

[1] Excerpts from site water quality monitoring dataset. Some of the pit lakes are treated with lime; the observed very alkaline maximum pH, and low minimum solute contents reflect treated waters.

## Conclusions

Laboratory derived data have been used as a basis to estimate solute production rates under field conditions. Whilst many assumptions and simplifications were necessary – it was possible to generate solute loadings for multiple AMD sources (pits and dumps) around the site that resembled current observations. The calculated ranges of chemistries for AMD impacted waters during operational, active closure conditions were found to lie within the range of chemistries observed, giving confidence that the estimates can be used to inform closure

planning. Incorporation of derived solute loadings in an overall site wide water and load balance was used to assess closure requirements and is described in a companion paper (Chapman et al. 2018).

## References

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