Acid Mine Drainage Risk Assessment to Inform Mine and Closure Planning

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Abstract

Using drillhole assay data to assess the risk of acid and metalliferous drainage (AMD) early in the planning of a mining operation can have a number of benefits. These include:

- Early identification of operational and closure AMD risks;
- Optimisation of geochemical characterisation programmes
- Early identification of mitigation and management measures (including engineering design);
- Early technical input to environmental approval applications;
- Preventing project delays due to late identification of environmental risks related to AMD and late commencement of lengthy geochemical testing programmes; and,
- Development and costing of closure strategies early in the planning process.

AMD assessments have been undertaken using drill-hole data (incorporating chemical assays and geological logging information) combined with interpretive geological models and mine planning information for a number of Australian iron ore operations. The approach has been implemented successfully for mine projects at various stages of development (for example, pre-environmental approvals to post-mining).

The example discussed herein illustrates the use of geological modelling tools (Vulcan, Leapfrog) to generate 3D visualisations of the distribution of sulfur (a key parameter indicative of AMD risk) within the pit shells. The final sulfur models were aligned with existing block models to allow examination of past, current and future mine plans in the light of AMD potential. Volumetric quantities of sulfur-bearing material reporting to waste rock dumps and ore stockpiles respectively were estimated. Small volumes representing sulfur-bearing 'hot-spots' were identified and maps were generated to determine the location of these hot spots on exposed pit walls, and assess closure scenarios with respect to AMD risk and anticipated post-mining water table levels.

This paper describes the overall assessment approach, the benefits of undertaking these assessments as early as possible in mine planning, and how the findings were used to inform the development of closure strategies at the sites.

Introduction

Acid and metalliferous drainage (AMD) assessments, if undertaken during the early stages of mine planning using data available within drill hole databases, have a number of benefits that will help improve the design and cost-efficiency of geochemical materials characterisation programmes, and provide early indication of the key AMD risks that may be present at a site. An understanding of these risks early in the planning stages of a project can provide valuable information that can help decision-making during pre-feasibility and feasibility level mine and closure planning, including:

- Pit optimization to avoid or reduce potentially acid forming (PAF) materials being exposed on the final pit walls;
- Mine scheduling to minimising of PAF waste production, and thus management and closure requirements;
- Limiting risks of impacts to groundwater and surface water, and supporting the design of monitoring programmes; and,
- Management of the pit at closure, considering options such as backfilling (overburden waste or in-pit tailings storage) or pit lake development.

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The assessment approach is consistent with the risk and outcome-based decision making framework outlined in the recent draft Guidelines for Mining Proposals in Western Australia (DMP, 2015). A draft guideline on materials characterisation requirements for mining proposals (DMP, 2016) outlines a phased approach to geochemical characterisation of subsurface materials as illustrated in Figure 1.

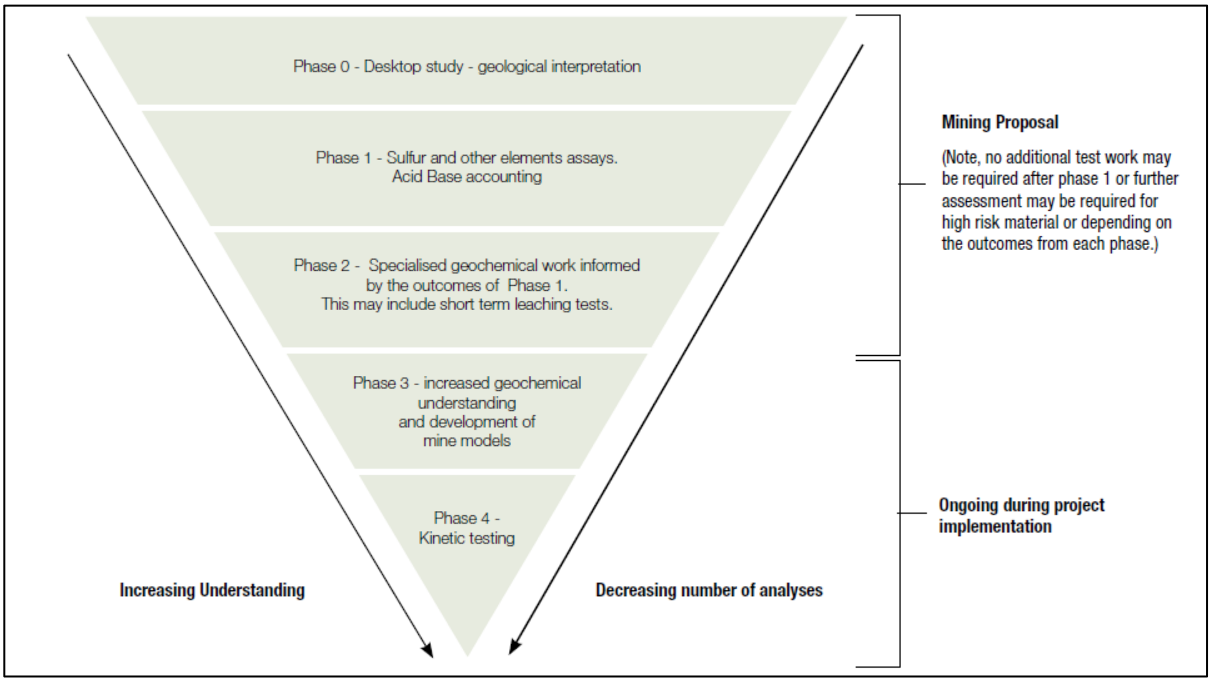

Figure 1: Phases of geochemical materials characterisation (DMP, 2016)

This paper describes how drillhole assay data have been used to develop an approach to assess the risk of AMD at an iron ore mine in Western Australia. The approach adopted in a previous case-study (Linklater et al., 2015) is discussed, in which geological modelling tools were utilised to build an understanding of the spatial distribution of sulfur within the mined void, helping to inform a preliminary assessment of AMD risk. Discussion is provided illustrating how the outcomes of the case study has been used to: i) focus ongoing geochemical characterisation activities; ii) aid mine planning and develop a mine waste management strategy; iii) provide a basis for scoping calculations to predict the possible quality of drainage waters; and iv) support closure planning.

Preliminary AMD Risk Assessment Approach

Source Assessment - Classification of PAF Materials

The propensity for mined materials to generate acid is a balance between the abundance of acid forming minerals (i.e. sulfides) and acid neutralising minerals (i.e. calcium and magnesium carbonates). In the current assessment, sulfur (S), was used to infer maximum potential acidity (MPA) based on the assumption that all sulfur is present in the form of reactive pyritic sulfide.

The project is located in the Pilbara region of Western Australia. The mineralised ore is located within the Dales Gorge Member of the Brockman Iron Formation which is part of the Early Proterozoic Hamersley Group. The Brockman Iron Formation is stratigraphically underlain by the Mount McRae Shale and Mount Sylvia Formation units, which are known to contain sulfidic mineralisation. Geologically, carbonate mineralisation is not widespread within overburden and waste materials which allowed the use of sulfur content as a primary indicator of the potential for acid generation. On that basis, a 0.2% sulfur cut-off value was utilised to differentiate PAF overburden material (Linklater et al, 2015). Materials with sulfur content below the threshold are considered to represent a low risk of acid generation. In addition, the Mt McRae Shale and Mt Sylvia units sourced from below the zone of oxidation were logged in the drillhole database as 'pyritic'.

The approach is considered to be conservative as it is likely to overestimate the proportion of PAF materials because:

(i) MPA has been overestimated by assuming all sulfur is present as sulfide sulfur - some sulfur may be present in other non acid generating forms, e.g. gypsum.

(ii) Credit has not been taken for acid neutralising capacity (ANC), which may be present in some lithologies. Whilst calcium (Ca) and magnesium (Mg) can be used as possible surrogates for carbonate-based ANC, there is uncertainty associated with the approach as some proportion of Ca and Mg may be present within other mineral phases, e.g. silicates.

Spatial and Volumetric Assessment

Geological modelling software (e.g. 3D modelling software[1] Leapfrog® and GOCAD) was used to process the drill-hole database to visualize the occurrence of the high sulfur zones within the pit volume and exposed on the final pit walls. In addition to sulfur data, the information required for modelling purposes included:

- Geological wireframes;
- Pre-mining and proposed final (as mined pit shells) topographies;
- Resource or mining block models; and,
- Pre-mining water table contours.

The resulting models were used to generate estimates of:

- Volumes of sulfur-bearing PAF material that would report to waste rock dumps and ore stockpiles; and,
- Pit wall rock surface exposure as a function of lithology and sulfur content.

The drill-hole assay data coordinates were then aligned with the block "mid-points" of the current mining models using Vulcan™ (3D modelling and mine planning) software[2], and blocks were classified according to the client's waste classification definitions, including a PAF waste category if >0.2 % sulfur.

Results

Geochemical Characteristics of Mined Lithologies

Statistical analysis of sulfur contents within each waste rock lithology were used to develop an understanding of the occurrence and distribution of PAF material and identify lithologies of concern. To account for materials that will be removed from site (i.e. ore), data were differentiated as ore or waste. Figure 3 illustrates the sulfur distribution for waste (from Linklater et al. 2015). The figure shows that, with the exception of pyritic waste, median sulfur content is generally low, below a 0.2% sulfur cut-off. The range of

[1] Leapfrog® Mining 3D modelling software was used for this study, which utilises a "toolbox" approach to 3D geological modelling, allowing processing, viewing and interpretation of drill-hole data. Leapfrog® is 3D geological modelling software which is designed to be used in the mining, exploration, environmental and geothermal energy industries. Leapfrog® is the registered trademark of ARANZ Geo Limited.

[2] Vulcan™ is 3D modelling and mine planning software, allowing users to validate and transform raw mining data into dynamic 3D models, mine designs and operating plans. Vulcan™ is trademark registered to Maptek™.

assays for some of the lithologies however exceeded the sulfur cut-off. In the case of pyritic wastes, maximum sulfur contents were up to 10%. In the absence of significant ANC this may indicate a risk of acid generation.

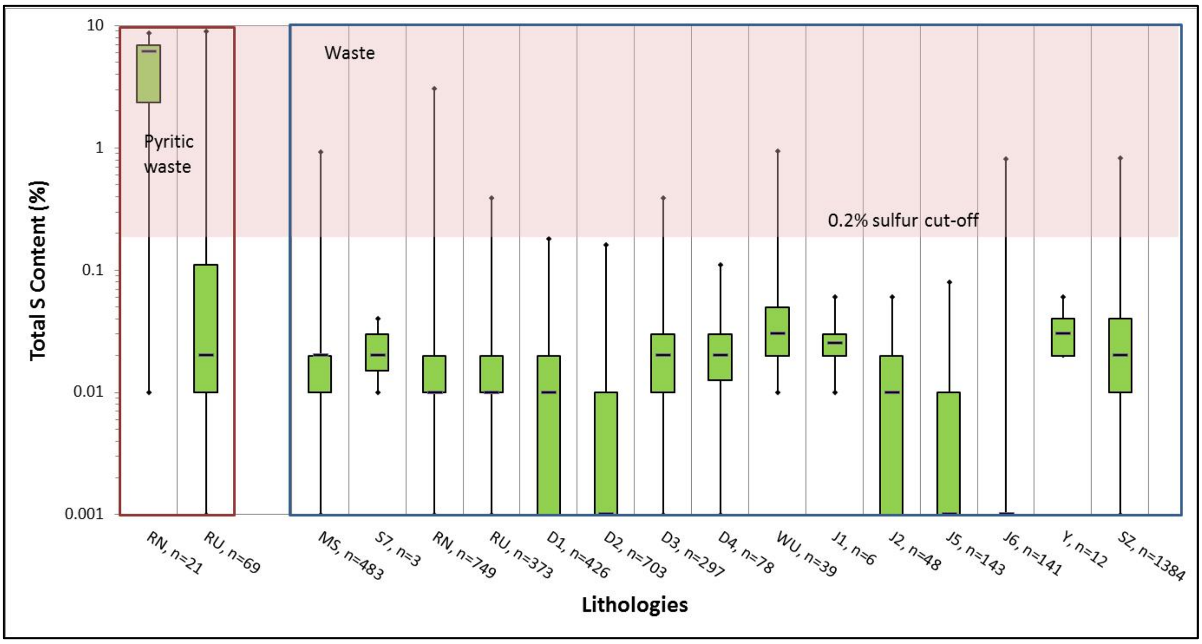

Figure 3: Box and whisker plots showing sulfur statistics in waste materials, by lithology (Linklater et al., 2015)

Note: At the site in question, two waste categories are identified (pyritic and non-pyritic)

The separate assessment of the sulfur distribution in ore materials was also undertaken to assess potential AMD risk from ore stockpiles. (Although not relevant to the case-study, the assessment of ore-grade materials could be used to infer potential geochemical characteristics of tailings.)

Waste Volumes and Mineralised Waste Management

Sulfur assay data within the pit shell were assessed against the sulfur threshold to determine the distribution of PAF-classed materials (Figure 4). PAF classified samples are shown in orange (>0.1% S) and red (>0.2% S). Where higher sulfur (PAF) samples were collected at shallow depths (e.g. 20 m) it is probable that the sulfur within these samples has been oxidised, i.e. is present as sulfate or hydroxysulfate. PAF samples that occur at greater depth, close to the pit floor and below the water table, are more likely to contain sulfide-sulfur.

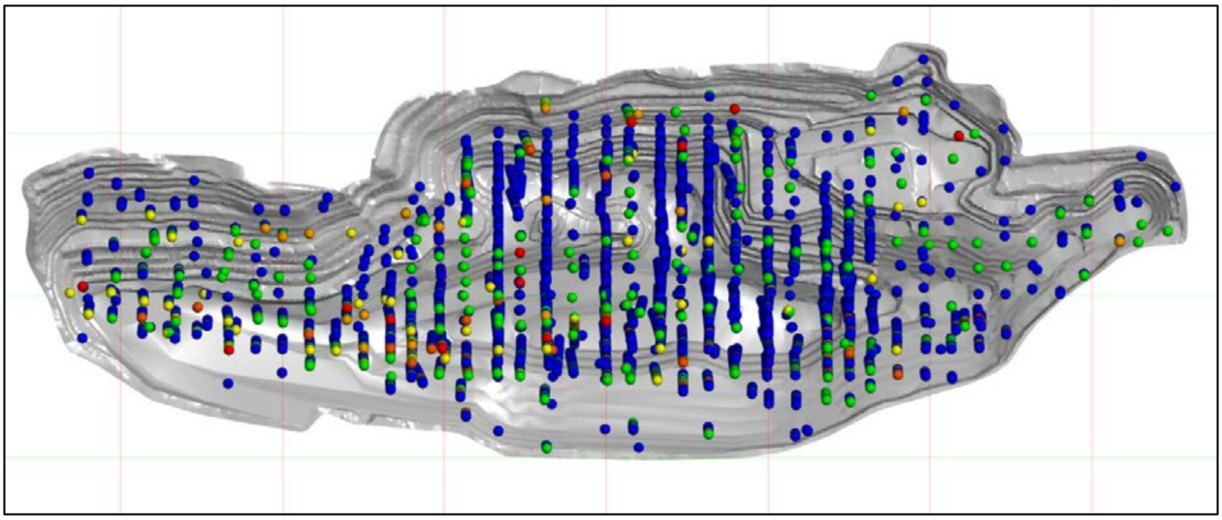

Figure 4: Image of pit shell showing spatial distribution of drill holes with sulfur data

Table 1 summarises the proportion of PAF samples for each lithology as identified in the waste rock assay dataset based on the 0.1% S and 0.2% S cut-off thresholds respectively. The highest proportions of PAF samples were present in the datasets of the 'pyritic' Mt McRae Shale units (RU and RN – up to 98%), however significant proportions of PAF samples (up to 10%) were also encountered within some of the 'non-pyritic' waste lithologies (e.g. the surface scree (SZ) and Upper Whaleback Shale (WU) units).

Since the samples were taken at fixed core intervals and the entire length of each drillhole was sampled, it is reasonable to assume that the proportion of samples that is PAF also represents the proportion of waste/overburden that is PAF for each lithology. The respective proportions of PAF were therefore multiplied by the waste rock volume of each lithology (Figure 5) to estimate PAF waste volumes to be mined (Table 1). Key lithologies with potential to generate acidity were identified, and also the relative contributions of each lithology to the total volume of PAF within the waste material.

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Table 1: Estimated proportions of PAF material in waste (Linklater et al., 2015)

Lithological Unit	% of waste volume	0.1% sulfur cut-off		0.2% sulfur cut-off	
		Proportion of PAF material in unit[1]	% of PAF material	Proportion of PAF material in unit[1]	% of PAF material
SZ	31%	10%	3%	5%	1.5%
WW	0.2%	[2]			
HJ	0.002%	[2]			
HE	0.05%	[2]			
Y	2%	0%	-	0%	-
J6	5%	1%	0.05%	1%	0.05%
J5	3%	1%	0.03%	0%	0%
J2	2%	1%	0.02%	0%	0%
J1	0.2%	5%	0.01%	0%	0%
WU	1%	10%	0.1%	5%	0.05%
D4	5%	5%	0.3%	0%	0%
D3	7%	5%	0.4%	1%	0.07%
D2	12%	1%	0.1%	1%	0.1%
D1	5%	3%	0.2%	1%	0.05%
RU	6%	5%/25%[3]	0.4%[4]	1%/5%[3]	0.1%[4]
RN	10%	5%/98%[3]	0.8%[4]	1%/95%[3]	0.4%[4]
S7	0.03%	0%	-	0%	-
S	10%	5%	0.5%	1%	0.1%
UN	0.4%	[2]			
Totals	**100%**		**5.9%**		**2.5%**

Notes:

[1] Proportion of PAF-classed material estimated on the basis of the percentile of the dataset that lies above the sulfur cut-off (0.1% or 0.2%).

[2] No data available for this volumetrically insignificant unit.

[3] General/un-oxidised 'pyritic' waste categories – as recorded in drill-hole logs

[4] Accounting for contributions from both general and pyritic waste categories

SZ – Surface Scree; Z – Tertiary Detritals; HJ – Weeli Wolli Iron Formation; HE – Weeli Wolli Dolerite; K – Dykes/Sills

Brockman Iron Formation: D1-4 – Units within the Dales Gorge Member; WU – Upper Whaleback Shale; J1-6 – Units within the Joffre Member; Y – Yandicoogina Shale

RU, RN – Mt McRae Shale (Upper and Nodular Zone, respectively); S – Mt Sylvia, undifferentiated; S7 - Mt Sylvia (Bruno's Band).

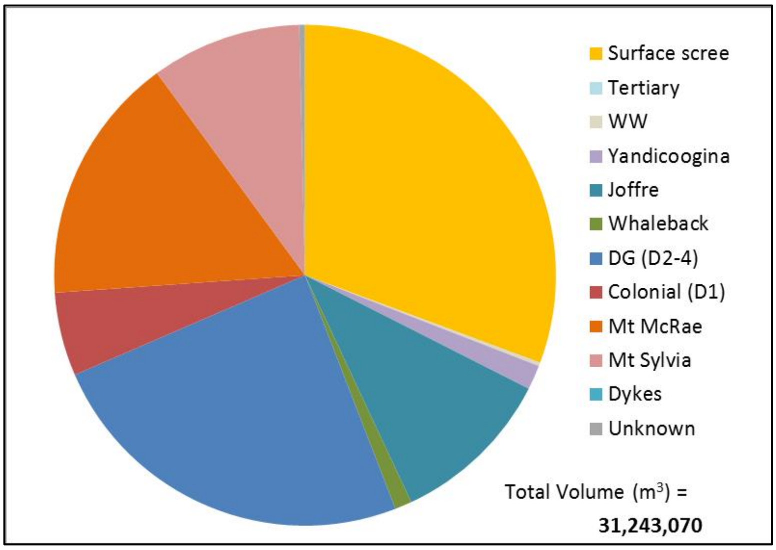


Figure 5: Pie-chart showing the lithological composition of waste rock to be mined from the pit

Pit walls and pit management

The risk of AMD from pit walls was evaluated based on maps of the pit wall surface lithology and sulfur content (PAF exposure), as shown in Figures 6 and 7, respectively.

The locations of exposed areas of higher sulfur [shown in orange (>0.1% S) and red (>0.2% S) in Figure 7] relative to the groundwater table and the position of boundaries between oxidised and unoxidised zones may have implications for both the operational management and also post-closure management of the pits. For example, during operations the mining could be scheduled so as to minimise the PAF wall rock that will be exposed to limit ongoing sources of solute release.

Post-closure pit management options include scenarios in which (i) a pit lake develops and (ii) the pit is backfilled, as shown in Figure 8. Assessment of the environmental performance of these options requires an understanding of the post-closure groundwater flow regime, the pit lake water balance, and the location and magnitude of potential sources of solutes.

Post-closure hydrogeochemical modelling determined that if a pit lake were allowed to develop, it would behave as a groundwater sink (i.e. evaporation would exceed inflows) with local groundwater flowing towards the pit. In this scenario, the solute loads inputs would include pitwall runoff and solutes content from inflowing groundwater. Where the water level rises to submerge exposed PAF areas, the rate of sulfide oxidation (and therefore solute production) would be reduced by orders of magnitude (due the reduction in supply of oxygen to the surfaces). However, any solute generated by the wall rocks and scree that accumulated in the pit benches would be mobilised and released to the pit lake.

Figure 7 shows that the majority of the exposed areas of PAF (orange and red shading) occurs on the pit floor and would be inundated by groundwater rebound after closure. A small area of PAF occurs close to the crest of the southern pit wall. If the pit lake level was to rebound to the lower bound level (shown by the white contour line on the figure) the area of PAF close to the crest would remain exposed and may represent an ongoing source of AMD.

Over time, due to evapo-concentration, the quality of the water would be expected to deteriorate. Since the pit would behave as a sink to groundwater, these loads would be contained indefinitely within the confines of the pit lake.

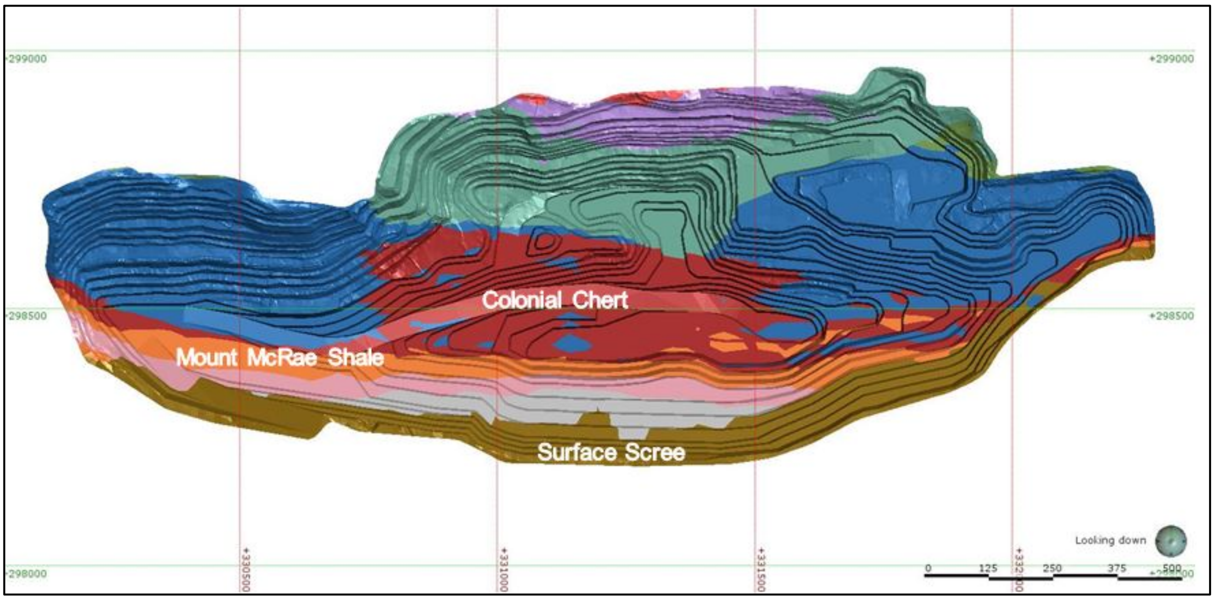


Figure 6: Leapfrog image of the pit shell, and showing lithological composition of the pit walls

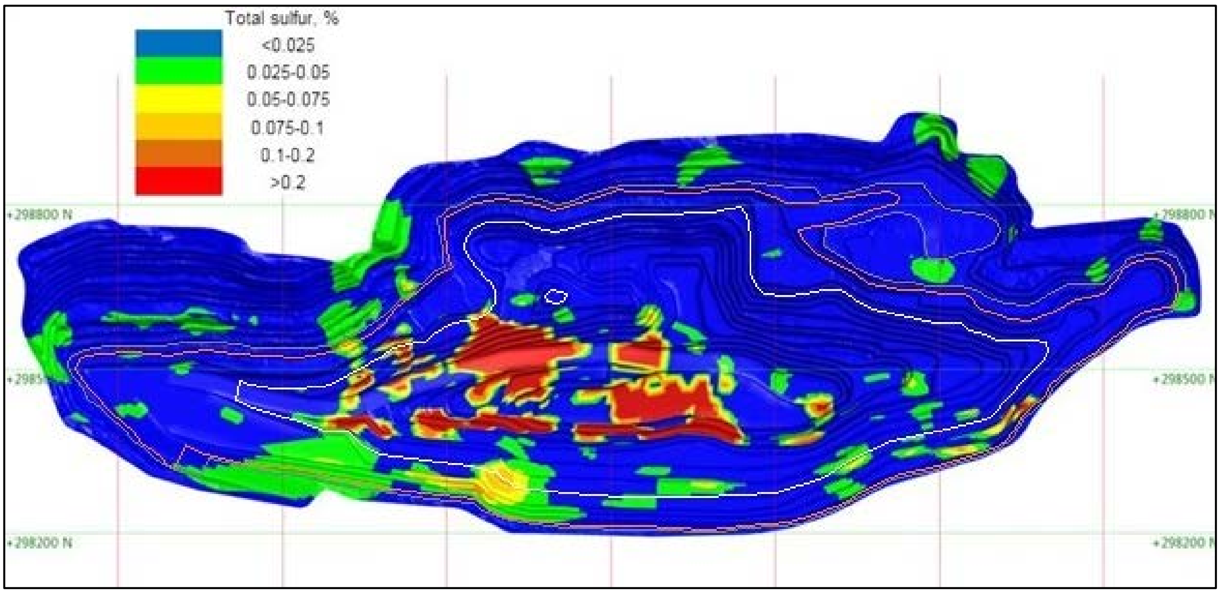
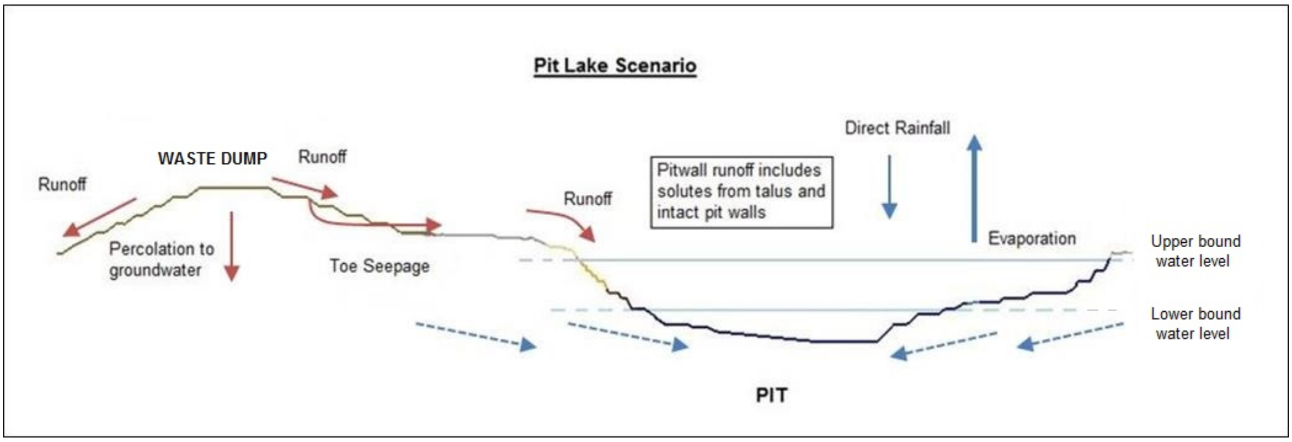


Figure 7: Leapfrog image of the pit shell showing the distribution of sulfur on the pit walls

Note: If the pit is backfilled (to 515 mRL) following the cessation of dewatering, the groundwater level is anticipated to recover to the pre-mining water table level (510 mRL).

Backfilling the pit to a minimum of 5 m above the water table would eliminate evaporation and the water level would rebound to the level of the pre-mining water table (grey contour line) and flow-through conditions would develop. As such, whilst backfilled PAF materials would cease to oxidise, the solutes present in the backfill will be released to the porewater and the porewater would be displaced over time. The composition and solute release potential of the backfill would have to be assessed to determine the overall solute release potential. Furthermore, if PAF material were present above the water table, the unsaturated backfill materials may represent ongoing sources of AMD.

The flow through conditions leading to the displacement of porewater over time would cause solute loads within the pit to migrate away from the pit in the direction of regional groundwater flow and may impact on downstream receptors.



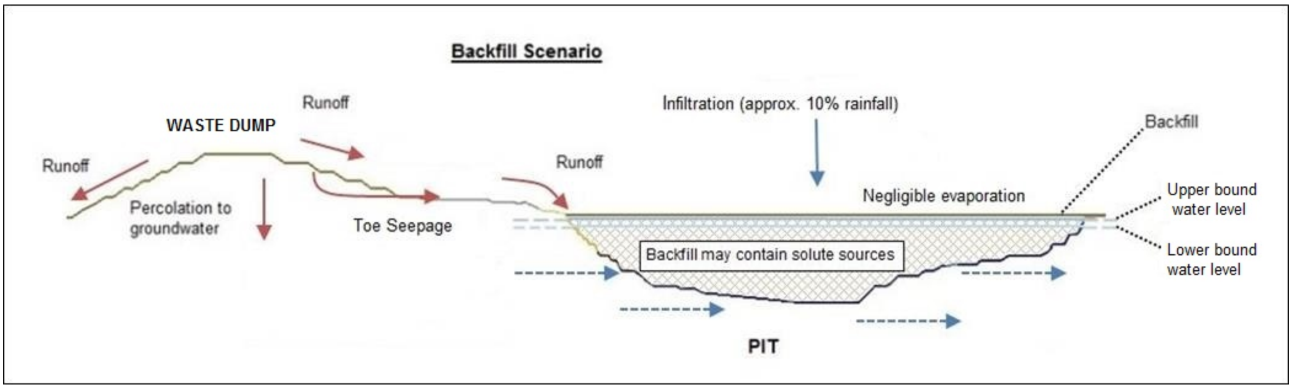


Figure 8: Schematic representations of a pit void showing (i) pit lake formation and (ii) backfilled pit closure scenarios

Optimisation of Geochemical Characterisation Programmes

The outcomes of preliminary assessments have been used to optimise the design of ongoing geochemical characterisation programmes for the site. The test programme is designed to address the current understanding of the material types to be managed, combined with the closure options that are under consideration. As these options include backfilling, the test programme includes saturated column test work (Figure 9), designed to assess leaching behaviour within saturated backfilled wastes. The programme also includes a range of static leach testing methodologies, designed to assess the effects of geochemical conditions such as pH, salinity and liquid:solid contact ratio on potential contaminant leaching.

Figure 9. Saturated column setup

Conclusions

Early assessment of drillhole assay data allows a project to be screened for AMD risk in advance of project feasibility assessment and final design. The outcomes also support the development of mine waste management strategies and closure planning.

The assessments can also be used to guide the scope of a detailed geochemical materials characterisation programme, facilitating optimised sampling and testing. The sampling for this programme (and parallel physical characterisation assessments) could be coordinated with other drilling projects (such as resource, geotechnical or hydrogeological drilling) to reduce costs.

Factoring in key AMD risks when appraising pit management options early in the life of mine, could reduce costs associated with waste materials management – enabling optimal environmental design of waste storage infrastructure, while also developing mine scheduling so as to limit waste stockpiling/handling costs.

Monitoring programmes could also be developed with improved understanding of the requirements of sampling locations, parameters and frequencies to support both operational and closure monitoring obligations, and be “data-ready” for risk-based assessments undertaken in support of environmental approvals.

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