

Review of mine waste capping methodologies for use in semi-arid regions of Queensland, Australia

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Abstract

The paper reviews conventional surface mine waste management practices and the development of capping methodologies over potentially contaminating mine wastes using soil covers. The paper then focuses on the store and release cover system appropriate for the tops of potentially contaminating mine waste storages in the semi-arid regions of Queensland, Australia. The treatment and drainage of the slopes of such mine waste storages are also described.

In Queensland, the Queensland Estimated Rehabilitation Cost User Guide (ERC User Guide) recommends soil cover layers and their thicknesses for the risk category assigned to stored mine wastes. The paper outlines the recommendations of the ERC User Guide and offers commentaries on their application in semi-arid regions of Queensland. It is noted that the ERC User Guide does not specify cover designs for different climatic settings, nor the materials or placement to be applied to the layers defined, which are key to the success of a cover system. Rather, the focus is on assigning a risk category to the stored mine wastes, covering both chemical and physical risks, and specifying the type and thickness of cover layers for that risk category. Attention should focus on the design, materials selection, and construction of mine waste covers to ensure that they are appropriate for the mine wastes stored and the climatic setting of the site. Further, the ERC User Guide does not specify the slope angle and treatment for waste rock dumps (WRDs), heap leach pads and tailings storage facilities, but presumes 'reprofiling', which forms the basis for estimating slope rehabilitation costs. Leaving angle of repose non-acid forming WRD slopes is not considered in the ERC User Guide, despite it being successfully applied at a number of mine sites in Queensland. The ERC User Guide states that "drainage is typically required on the finished cap to ensure that surface water drains off the cap", despite this concentrating rainfall runoff.

Keywords: *cover system, estimated rehabilitation cost, mine waste storages, rehabilitation, slope treatment*

1 Introduction

The well-accepted overarching requirement for mine sites post-closure is safe, stable, and non-polluting landforms in perpetuity that can sustain an agreed post-closure land use or ecological function (Department of Environment and Science [DES] 2019; DMIRS 2020). However, very few mines have successfully been rehabilitated, let alone relinquished.

The management and control of seepage from potentially contaminating surface waste rock dumps (WRDs) and surface tailings storage facilities (TSFs) is a significant issue for the mining industry during the operation and following the closure of surface mines, carrying high and long-term costs. For industry, government, and other stakeholders, developing appropriate management and controls is imperative to retaining the industry's financial and social licences to operate. Controls include the segregation and encapsulation of potentially contaminating waste rock on placement in the dump, maintaining potentially contaminating tailings near saturated, and appropriate WRD and TSF cover systems and slope treatments. Regulatory financial assurance is based on the estimated cost of capping WRDs and TSFs, while operators attempt to minimise the cost of rehabilitation, placing the two groups in conflict. Unfortunately, the two groups' aims and methods are often in conflict, which may lead to a failure to achieve effective rehabilitation results post-closure. All too often, the focus is on securing 'financial assurance' in the form of a bank guarantee or cash bond, which can inhibit rehabilitation aimed at reducing the liability.

2 Conventional surface mine waste management

The conventional management of waste rock and tailings from surface mines is described in the following sections.

2.1 Surface waste rock management

Both WRDs and the processing plant are typically located as close as practicable to the egress from the open pit to minimise the haulage cost for waste rock and ore, while tailings facilities are typically located further from the pit and the plant because the cost of pumping thickened tailings is on the order of 3.5 times less than the cost of hauling waste rock and ore (CIPEC 2005). However, if waste rock is used to construct tailings dams, the costs of the TSF may increase depending on the haul distance, forcing consideration of both the tailings and the waste rock storages being located close to the pit.

Waste rock produced on open pit mining is expensive to haul, and about 5 times more expensive to haul up a ramp (typically at a slope of 10% or 10H:1V) than on the flat because of the reduced speed (from a maximum of 60 kph on the flat to between 10 and 15 kph on ramps), substantial increase in fuel consumption up a ramp, and greater tyre wear up a ramp. To minimise waste rock haulage costs, surface WRDs are located as close as practicable to the egress from the open pit, and waste rock is transported horizontally until it becomes less expensive to go up a ramp to the next lift, and so on, as shown schematically in Figure 1 (Williams 2019). As a result, unless steps are taken to avoid it, the weathered (or oxidised) surficial overburden is dumped on the base of the WRD and close to the pit, while any sulfidic waste rock (depicted in red in Figure 1) from deeper in the pit below the groundwater table is dumped further away from the pit and higher in the dump.

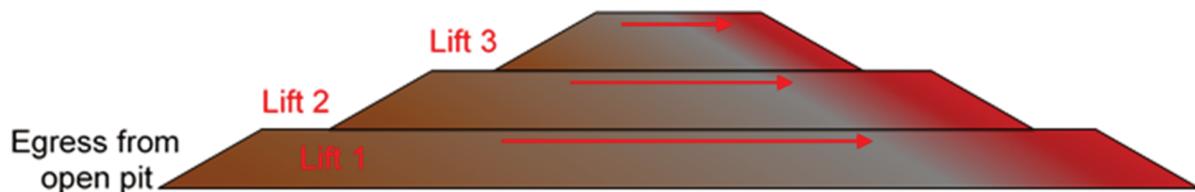


Figure 1 Schematic of typical waste rock dumping

In addition, the conventional end-dumping of waste rock in a surface dump produces ‘oxidation reactors’, as shown in Figure 2 (International Network for Acid Prevention [INAP] 2009), involving a base rubble zone formed by the ravelling of boulders, alternating but discontinuous coarse- and fine-grained angle of repose layers, and a haul truck–compacted, trafficked surface on the tops of each lift. The base rubble zone allows the ready ingress of oxygen, which passes up the coarse-grained angle of repose layers from which it diffuses into adjoining fine-grained angle of repose layers. Oxidation is dominant in the fine-grained layers, which have the highest surface area to volume ratio, and these layers store the most water, until breakthrough seepage occurs. These conventional waste rock storage practices exacerbate the potential for future acid and metalliferous drainage (AMD), challenging rehabilitation.

Potentially contaminating waste rock (such as such as potentially acid-forming [PAF] sulfidic materials) should be encapsulated within non-contaminating wastes rock (such as non-acid forming [NAF] or acid-neutralising capacity [ANC]), and a cover placed to limit oxygen ingress and the net percolation of rainfall (Williams 2019; Figure 3).

Provided that it will not sterilise future resources, consideration may be given to backfilling the open pit with waste rock, particularly with PAF waste rock that would pose a risk of AMD if placed in surface WRDs.

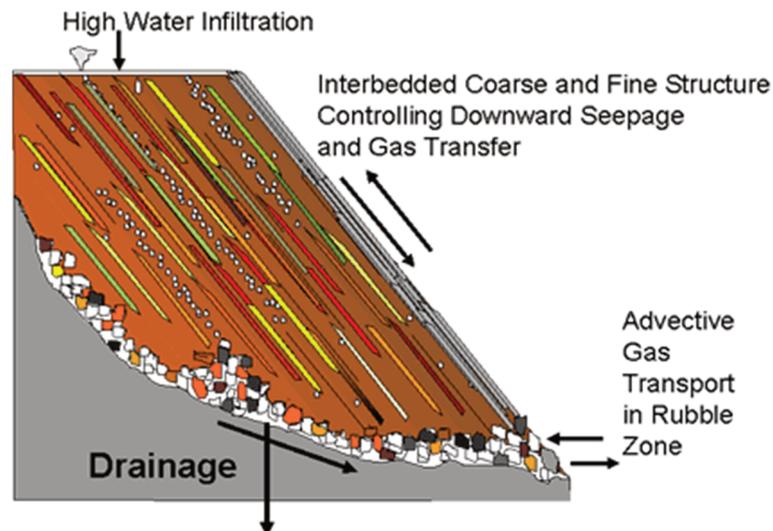


Figure 2 Conventional end-dumping of waste rock in a surface dump

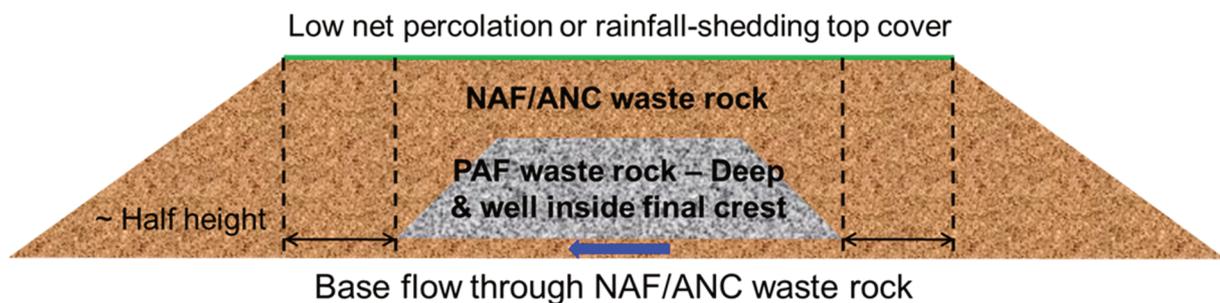


Figure 3 Encapsulation and covering of potentially contaminating waste rock

Closure risks and challenges for surface WRDs include slope instability, possibly geotechnical or, more likely, erosional, particularly in a dry climate if the slope is flattened and topsoiled. In addition, differential settlement of the loosely placed waste rock can affect the slope profile and drainage. The spontaneous combustion of high-sulfide waste rock can lead to swelling because the secondary minerals formed occupy more volume, while the spontaneous combustion of sulfidic coal coarse reject or spoil will lead to collapse because of the combustion of carbonaceous material.

Seepage water quality from WRDs can be saline and/or acidic, typically following a geochemical lag and/or a hydrological lag (taking time for the dump to wet up sufficiently and requiring significant rainfall events for seepage to emerge; Williams 2020). Seepage will likely emerge at low points around the toe of the WRD, or report to the foundation beneath the dump, and potentially to groundwater. Runoff from WRDs could carry erosion sediment and any contaminants.

2.2 Surface tailings management

Figure 4 (adapted from Davies & Rice 2001) shows five different tailings dewatering options, the advantages and disadvantages of each option, and the relative levels of capital (capex), operational (opex), and rehabilitation expenditure required for each option. The net present value approach, which prioritises the minimisation of capex and opex over the minimisation of rehabilitation costs, favours the centrifugal pumping of thickened tailings to a TSF.

The conventional approach to tailings management is to thicken the tailings to the extent that they can be pumped using robust and inexpensive centrifugal pumps delivering the tailings by pipeline to a surface TSF, where the tailings are conventionally deposited sub-aerially (i.e. above water and on the surface), forming a beach (Williams 2014).

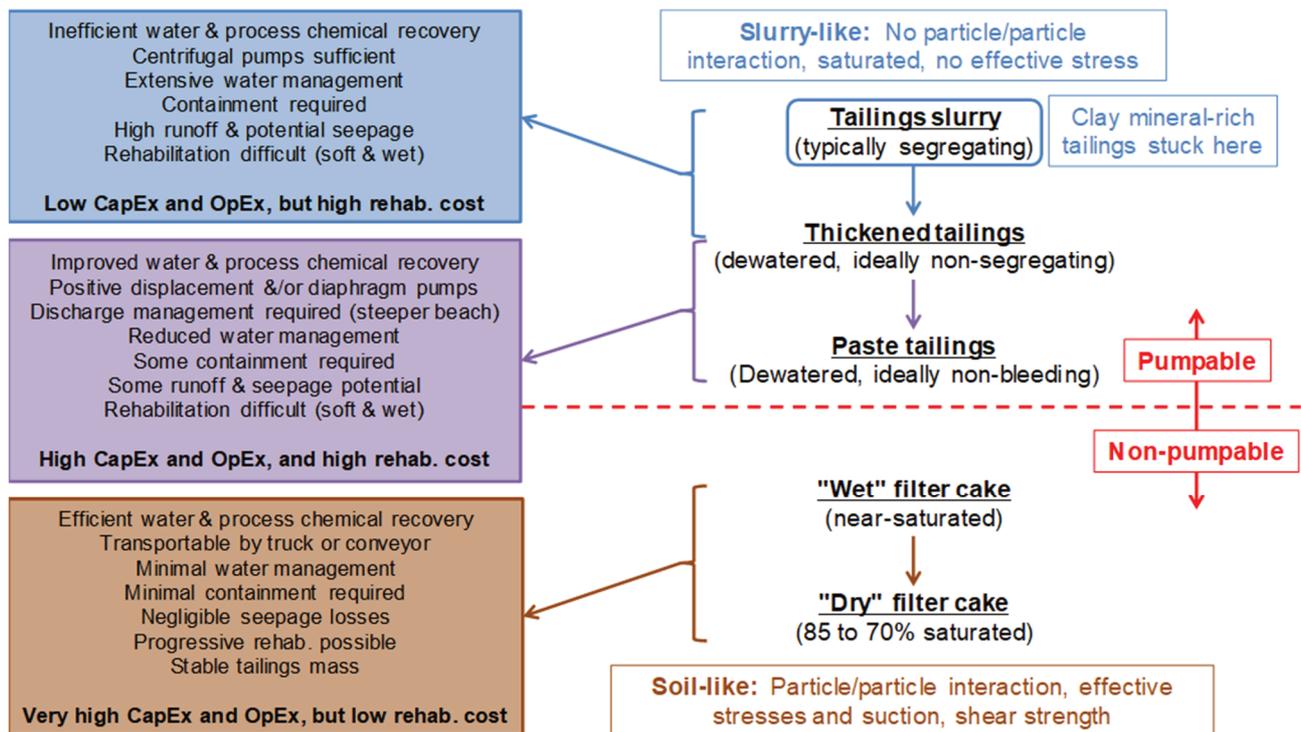


Figure 4 Tailings continuum from slurry-like to soil-like

The types of tailings containment and method of dam construction vary globally, according to the climatic, topographic, and seismic settings of the site. Upstream construction, using tailings where possible, is widely employed in southern Africa, Australia, and the southwest of the USA, which have in common a dry climate (allowing progressive desiccation of tailings placed in thin layers), plus generally low topographic relief (resulting in low height tailings dams, large footprints, and slow rates of rise), and generally low seismicity.

Processing may include lime or acid addition, leaving residual buffering capacity or acidity within the tailings. Conventional tailings deposition as a slurry limits oxygen availability, while surface desiccation allows slow oxygen ingress to shallow depth. The limited supply of oxygen and ready supply of water means that the geochemical lag is likely to govern over the hydrological lag for tailings, although any available acid neutralisation capacity will lengthen the geochemical lag, until it is consumed (Williams 2020).

Storage facilities for potentially contaminating tailings can be lined and provided with underdrainage to limit AMD. The liner limits net percolation into the foundation and through the tailings dam, while the underdrainage serves to consolidate the tailings above the liner, increasing their density and reducing their hydraulic conductivity, thereby adding to the effectiveness of the liner by reducing the hydraulic gradient.

Potentially contaminating tailings, such as PAF tailings, can be managed operationally by depositing the tailings in thin layers (typically less than 300 mm), cycling deposition to allow some desiccation (over days rather than weeks), but restricting the desiccation prior to the deposition of the next layer of wet tailings to maintain at least 85% saturation in the tailings, and hence limit oxidation and potential AMD.

A tailings hardpan, or compacted tailings surface, will act as a sealing layer, limiting the net percolation of rainfall and the uptake of salts into the cover. Reduced net percolation will diminish the potential seepage of contaminants. Reduced tailings permeability will also inhibit upward flow and hence the uptake of salts into an overlying growth medium cover.

Agnew (1998) investigated the natural formation of tailings hardpans as possible inhibitors of tailings AMD, contaminant release and dusting, and found that the effectiveness of hardpans in inhibiting acid generation is dependent on their reducing oxygen diffusion and rainfall infiltration, while maintaining long-term erosional stability. Hardpans can have a permeability 10 to 100 times lower than that of uncemented tailings,

and an oxygen diffusion rate up to 1,000 times lower, causing them to maintain a high degree of saturation, and restrict the movement of water and oxygen.

Negligible uptake of salts from saline seawater-neutralised red mud at Queensland Alumina at Gladstone was demonstrated in an instrumented column test carried out at The University of Queensland (Zhang et al. 2018). Over a 2-year monitoring period, there was negligible uptake of salts into the cover. The compacted red mud remained unsaturated, with a hydraulic conductivity less than 10^{-10} m/s (less than 3 mm/year), limiting flow and hence any potential movement of salts, while rainfall and evaporation cycled freshwater in the much more permeable overlying cover material.

Tailings storage facilities are necessarily left uncovered during operation and are periodically re-wetted by fresh tailings and/or rainfall. Hence, desiccation and any oxidation may be periodic and limited. On closure, the tailings surface in a dry climate is able to desiccate, allowing the oxidation of any sulfidic tailings. Subsequent rainfall infiltration may leach the oxidation products from the surface layer, making them more benign. A low permeability cover will limit the further desiccation and any oxidation of the surficial tailings, and the net percolation of rainfall. The excess storage of surface water from heavy rainfall events would recharge seepage and is best avoided by providing a spillway.

Closure risks and challenges for surface TSFs include dam geotechnical instability; erosion, particularly in a dry climate if slope is flattened and topsoiled; and differential settlement of the tailings, affecting their slope profile and drainage. Seepage water quality from TSFs can be saline and/or acidic, or alkaline, likely after a geochemical lag as the tailings desaturate and consume any neutralising capacity. Seepage can occur into the foundation beneath the TSF and/or through the dam, depending on the reducing permeability of the deposited tailings and the permeability of the foundation and the dam. Runoff is generally captured in the decant pond, recharging seepage, unless it is released via a spillway.

3 Soil covers over potentially contaminating mine wastes

The tops of WRDs (and heap leach dumps) and TSFs can be covered to limit the generation and transport of any contaminants. Guidance on the choice of cover type for the tops of potentially contaminating mine waste storages for different climatic settings is provided by the GARD Guide (INAP 2009; Figure 5). The role of covers on potentially contaminating mine wastes is to: (i) limit oxygen ingress, and/or (ii) limit net percolation of rainfall. In a dry climate, such as much of Queensland, a 'store and release' cover is appropriate and recommended by the GARD Guide (INAP 2009) to limit net percolation of rainfall and hence the potential for contaminated seepage.

The GARD Guide (INAP 2009; Figure 6) also provides schematics of soil cover designs, as summarised in Table 1, which increase in complexity, construction difficulties, potential performance, and cost, from left to right. These schematics have generated much confusion, particularly in Australia. Cover I, indicating a thicker single layer of growth medium than the Base Case, is inferred to be 'better' than the Base Case. However, thicker is not necessarily better. A thick "native material or barren waste or oxidised waste" layer intended to serve as a growth medium can lead to the infiltration of rainfall to a depth that makes it inaccessible to revegetation. This can also lead to increased net percolation into underlying PAF waste rock or tailings, and hence the generation of acidic seepage. The net result may be worse than having no cover at all, since the cover would constitute a 'sponge' that would increase rainfall infiltration compared with a compacted top of a WRD, or a desiccated or compacted tailings surface.

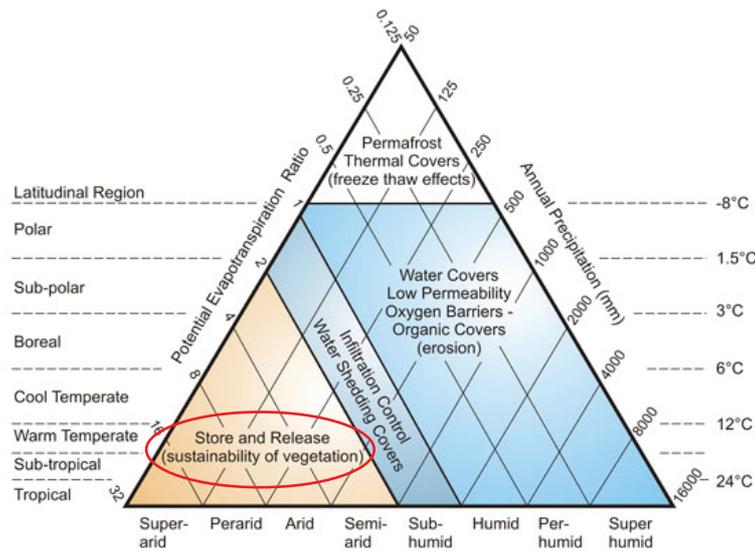


Figure 5 Choice of cover based on climate

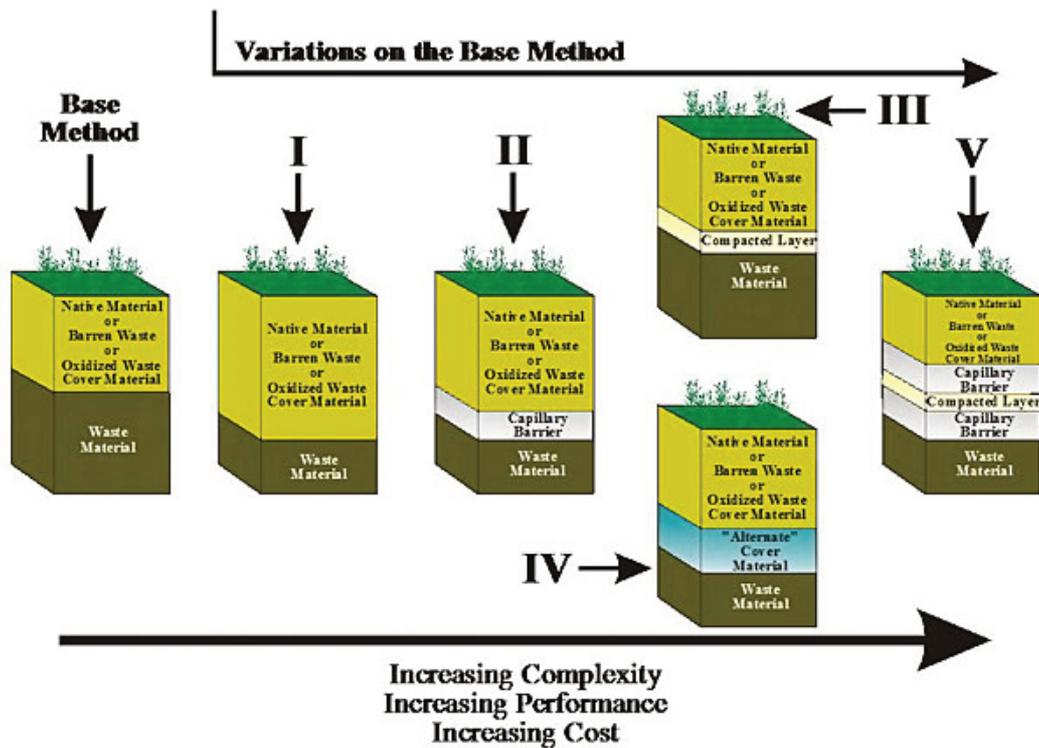


Figure 6 Sample soil cover designs

Cover II adds a capillary barrier (or break) beneath the growth medium, which may be desirable to limit the uptake of any salts from the underlying waste rock or tailings into the growth medium. A capillary barrier relies on a material that limits saturation and flow driven by capillary action and must be carefully selected and sized to ensure that it is effective in the short and long terms. Suitable capillary barrier material is clean gravel.

Run-of-mine waste rock would likely not be suitable for use as a capillary barrier, without crushing of coarse-grained particles and washing to remove fines. A capillary barrier is a 'drain', and so should be overlain by a sealing layer to limit the net percolation of rainfall into the underlying wastes. Clean gravel would require a thickness of greater than 200 mm to remain effective as a barrier.

Table 1 Summary of soil cover designs

No.	Description	Comment
Base	Natural, barren, or oxidised growth medium	Basic cover to cap the potentially acid-forming (PAF) wastes and serve as a growth medium (benign wastes may revegetate naturally)
I	Base case, but thicker	A thicker growth medium, but too thick a layer may allow deep drainage to below the root zone and into the PAF wastes
II	I, but including a capillary break	Capillary breaks are intended to limit the evapotranspirative uptake of contaminants from the PAF wastes up into the cover, but need to be clean (minimal fines) gravel-sized
III	I, but underlain by a compacted clay layer	The compacted clay layer provides a seal to hold up rainfall infiltration for access by plants and to limit net percolation into the PAF wastes, removing the need for a capillary break
IV	I, but underlain by an alternative sealing layer	A geomembrane or geosynthetic clay liner could be used in the absence of clay
V	Compacted layer sandwiched between two capillary breaks, without or with a growth medium	Based on the cover with capillary barrier effects employed at the Les Terrains Aurifères mine site over sulfide tailings in a net positive precipitation climate in Québec, Canada, where even there it failed over time

The capillary barrier must allow for the possible infiltration of fines from the overlying growth medium, which would render it less effective over time. The particle size of the capillary barrier must be matched to that of the overlying growth medium, using filter criteria to ensure that the infiltration of fines into the capillary barrier is limited by ‘arching’ between particles. Finding suitable material for an effective capillary break and ensuring its sustainability are challenging.

Cover III adds a compacted (clayey) sealing layer beneath the growth medium, which is desirable, particularly for a store and release cover, to ‘hold up’ rainfall infiltration within the overlying ‘rocky soil mulch’ layer. Cover IV is a variation on Cover III, in which the compacted layer is replaced by an ‘alternative’ sealing layer, such as a geomembrane, bituminous geomembrane, or geosynthetic clay liner (GCL). A seal could also potentially be achieved by compacting the top of a WRD or, for tailings, by the development of a hardpan on sulfidic tailings, or by compaction of the tailings’ surface.

Cover V incorporates three layers separating the growth medium from the waste rock or tailings, comprising a compacted fine-grained layer sandwiched between two capillary barriers. This cover was apparently based on the cover with capillary barrier effects (CCBE) applied to a specific situation in Canada. Bussière et al. (2006) described a CCBE employed at the Les Terrains Aurifères (LTA) mine site sulfide tailings impoundment, near Malartic, Abitibi, in Québec, Canada, in a net positive precipitation climate.

The CCBE constructed on the LTA tailings in 1998 comprises 500 mm of sand (a capillary barrier) placed on the sulfidic tailings, overlain by 800 mm of fine-grained, non-acid-generating tailings (a moisture-retaining layer), which is in turn overlain by more than 300 mm of sand and gravel (protection and drainage layer). The design objective was to maintain a minimum degree of saturation of 85% in the moisture-retaining layer to effectively reduce the oxygen flux from the atmosphere to the acid-generating tailings. Near saturation of the moisture-retaining layer was to be maintained by a combination of enhanced rainfall infiltration and suction in the underlying capillary barrier.

The intention of the sand and gravel surface layer was to maximise rainfall infiltration and to limit revegetation. The same cover was applied to the side slopes of the tailings impoundment (also comprising sulfidic tailings). The cover initially functioned as intended on the top of the impoundment, which initially remained unvegetated, but not so well on the side slopes, due to gravity drainage.

Smirnova et al. (2011) investigated volunteer revegetation on the LTA CCBE, which commenced the year after construction. Eight functional groups of plants were identified, with herbaceous plants being the most abundant. Of the 11 tree species identified, the four most abundant were poplar, paper birch, black spruce, and willow. Root excavation showed that tree roots penetrated the moisture-retaining layer, with an average root depth of 400 mm and a maximum root depth of 1.7 m.

Bussi re et al. (2015) reported that after 10 years, the LTA CCBE was effective in reducing the oxygen flux from the atmosphere to the acid-generating tailings. However, the quality of the seepage from the tailings impoundment still did not meet Qu bec water quality standards, and dolomitic drains were constructed as a passive treatment. Views of the LTA tailings impoundment before CCBE construction in 1998, after CCBE construction in 1998, and 10 years later in 2007 are shown in Figure 7 (INAP 2009).



Figure 7 Views of LTA tailings impoundment before CCBE construction in 1998, after CCBE construction in 1998, and 10 years later in 2007

The CCBE was designed for a specific purpose, in a net positive precipitation climate, and appears to be the only Cover type V double capillary barrier cover applied in practice. Double capillary barrier (or break) covers have been promoted by some regulators in Australia, notably in Queensland. This is perplexing, since the majority of mine sites in Queensland, and elsewhere in Australia, are in semi-arid to arid climates, for which the GARD Guide (INAP 2009; Figure 5) recommends a store and release cover.

4 Store and release cover for dry climates

The store and release cover (Williams 2006; Williams et al. 1997) is shown schematically in Figure 8. The key elements of a store and release cover, developed for seasonal, dry climates, such as that which exist in much of Queensland, are (i) a thick, loose 'rocky soil mulch' layer with an undulating surface to store the wet season rainfall without inducing runoff; (ii) an effective sealing layer at the base of the cover to 'hold up' rainfall infiltration; and (iii) the appropriate choice of sustainable revegetation to release the stored rainfall during the wet season, through evapotranspiration. The required thickness of rocky soil mulch will depend on the wet season rainfall pattern and the rooting depth of the vegetative cover and is typically 1.5 to 2 m thick. Too thick a growth medium could lead to rainfall infiltration beyond the reach of the revegetation. In a dry climate, store and release covers are more robust than rainfall-shedding covers.

The nominal 500 mm thick compacted sealing layer should achieve a saturated hydraulic conductivity of less than 10^{-8} m/s (equivalent to a potential percolation rate of less than 300 mm/year, when water is available), so that in its usual unsaturated state in a dry climate its hydraulic conductivity will be less than 10^{-10} m/s (a potential percolation rate of less than 3 mm/year). In Queensland's typically dry climate, rainfall occurs on about 30 days/year, so that water may be available on top of the sealing layer for perhaps 10% of the time, reducing the potential percolation rate to less than 30 mm/year, or less than 5% of the typical average annual rainfall, similar to the typical natural percolation rate. High net percolation will be associated mainly with extreme rainfall events. The cover should cycle annually between wet and dry states without a net wetting up (which would lead to net percolation) or drying out (which would cause revegetation dieback and subsequent rainfall-induced erosion).

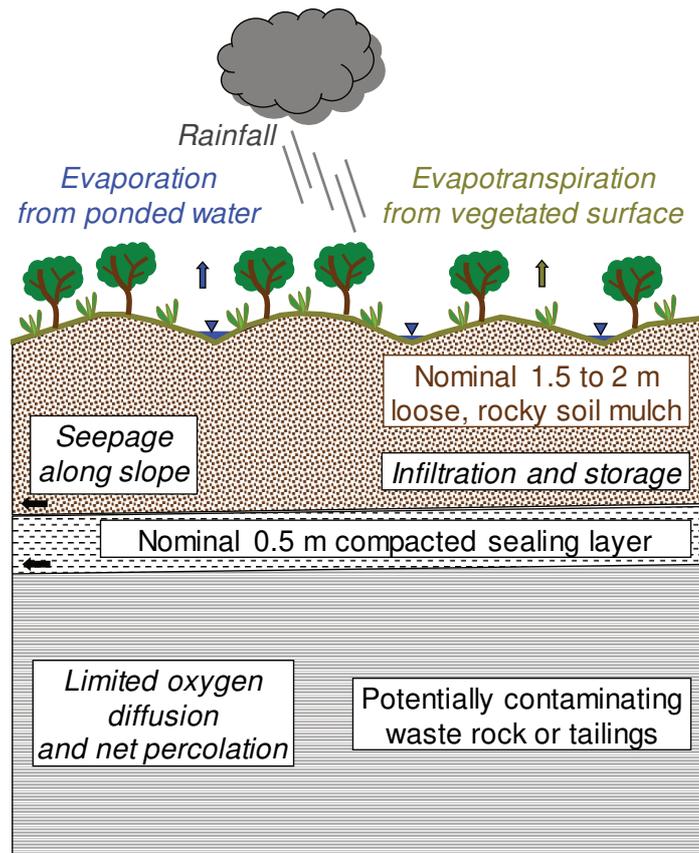


Figure 8 Schematic of store and release cover

In Queensland's generally arid to semi-arid climate, a mixed eucalypt tree cover represents the only sustainable means of achieving the required evapotranspiration rates from a store and release cover to handle extreme rainfall events and be sustainable in the long term.

There is ongoing concern and debate about the effect of tree roots on cover integrity on the tops of mine waste storages. Tree roots can potentially penetrate through the cover thickness towards the underlying, potentially contaminating waste rock or tailings. However, the compacted top of a WRD and a tailings hardpan or compacted tailings are essentially root barriers. This mitigates the penetration of tree roots to depth. Instead, the tree roots would grow laterally through the overlying cover.

Since the rocky soil mulch is loose and granular, trees are unlikely to promote cracking and the development of preferred seepage pathways through the cover. The height of trees will be limited by the climate, and by the thickness, and water-holding and nutrient capacity of the rocky soil mulch. Sufficient rocky soil mulch thickness and the limited tree height that results will limit the possibility of wind blow down and possible threat to the integrity of the cover. Should wind blow down of shrubs and trees occur, the limited rooting depth will limit the impact on the cover, and the coarse-grained rocky soil mulch will tend to self-heal.

5 Slope treatment and drainage

There is a widely held belief that mine waste slopes need to be flattened to ensure geotechnical and erosional stability. However, angle of repose waste rock slopes have a calculated Factor of Safety against geotechnical instability of greater than 1.2, and erode less than flattened and topsoiled slopes where revegetation is inadequate. Flattening steep mine waste facility slopes to moderate slope angles (of between 3H:1V and 6H:1V) may not reduce erosion. Mine waste storage facility slopes have a fixed height, so that any slope flattening will increase the slope length or catchment. Dozing to achieve flattening will crush and bury large particles, leading to a smoother surface texture and greater runoff. Hence, slope flattening will increase

erosion. Slope flattening or reprofiling may, however, be required for safe access, revegetation, or for cultural and aesthetic reasons.

Mine waste facility slope treatment options include:

- Leaving slopes at the natural angle of repose that the material ravel at (typically 35 to 40°, increasing for more blocky, durable rock), which may be suitable for durable NAF waste rock, or for NAF waste rock that supports revegetation, either natural or planted, and may better match natural hillslopes, particularly mesa-like features.
- Pushing down lower slope benches, while leaving upper slopes at the angle of repose to form a concave slope profile, matching erosionally stable natural slope profiles.
- Flattening angle of repose slopes to match surrounding natural hillslopes, incorporating variability.

The erosion of slopes is a function of the surface texture and revegetation (So et al. 1998). A grass cover needs to extend over the majority of the surface of a slope to be effective in limiting erosion, and during Queensland's long dry season, this cannot be ensured. Further, extended droughts cause revegetation dieback. This has implications for the use of erodible, fine-grained topsoil on slopes. Erosion resistance under such climatic conditions requires a rocky surface texture on slopes.

The drainage of the tops of mine waste storage facilities over the side slopes concentrates rainfall runoff about 10-fold, and its capture in constructed drains can concentrate it a further 10-fold, so that a 10 mm rainfall event generates 1,000 mm of runoff in constructed drains. Such concentration of rainfall runoff cannot be accommodated in standard design, as has been widely demonstrated at mines throughout Queensland, and is not recommended (Williams 2014).

6 ERC User Guide—approach to capping mine waste storage facilities

The ERC User Guide focuses mainly on the capping of the tops of mine waste storage facilities, and the estimated cost of such capping for financial assurance purposes, with little attention paid to the treatment of slopes and surface drainage provisions.

The ERC User Guide (DES 2019) is based on assigning a risk category to WRDs, heap leach pads, and TSFs, according to the following scale:

- High:
 - PAF and other highly reactive materials, leading to contaminated seepage causing environmental harm.
 - For TSFs, also including poorly consolidated and low-strength tailings, requiring a liner, and dams greater than 30 m high.
- Medium:
 - Moderately reactive and hypersaline materials.
 - For TSFs, also including low-strength consolidated tailings, and dams 15 to 30 m high.
- Low:
 - Low reactive and moderate to low salinity materials.
 - For TSFs, also including moderate-strength consolidated tailings, and dams less than 15 m high.
- Very Low:
 - Benign, non-reactive and low-salinity materials.
 - For TSFs, also including moderate-strength consolidated tailings, and dams less than 15 m high.

The ERC User Guide defines the following in relation to covers or caps for WRDs, heap leach pads and TSFs:

- Working layer:
 - Not required for WRDs or heap leach pads.
 - A ‘working rock layer’ over tailings is specified to provide a ‘stable surface’ for the cap.
- Capillary break:
 - Capillary break layer to mitigate salt uptake into the vegetation surface.
- Low permeability layer:
 - Low permeability layer (typically clay) to prevent infiltration of surface water into the waste.
- Top rock layer:
 - Presumably to provide water storage and rooting depth for vegetation, although this is not made clear in DES (2019).
- Top layer:
 - Growth media (typically topsoil) and revegetation.

The requirements of these layers are specified in Table 6-2 in DES (2019). Based on Table 6-2, the inferred cover designs are as indicated in Table 2.

Table 2 Summary of implied DES (2019) soil cover designs

Risk category	Waste rock dumps (and heap leach pads)	Tailings storage facilities
High	0.6 m capillary break, overlain by 0.5 m low permeability layer, overlain by 1.5 m rock, overlain by 0.15 m Topsoil (total 2.75 m)	0.5 m working layer, overlain by 0.6 m capillary break, overlain by 0.5 m low permeability layer, overlain by 1.5 m rock, overlain by 0.15 m topsoil (total 3.25 m)
Medium	0.3 m capillary break, overlain by 1.0 m rock, overlain by 0.15 m topsoil (total 1.45 m)	0.5 m working layer, overlain by 0.3 m capillary break, overlain by 1.0 m rock, overlain by 0.15 m topsoil (total 1.95 m)
Low	0.5 m rock, overlain by 0.15 m topsoil (total 0.65 m)	1.0 m rock, overlain by 0.15 m topsoil (total 1.15 m)
Very Low	No cover required	No cover required

7 Commentary on ERC User Guide for Queensland

Importantly, in a decision by the Land Court of Queensland (2021), the purpose of the ERC User Guide is “to provide guidance”, informed by expert opinion, with the prime purpose of minimising the potential for environmental harm, rather than adopting a ‘default’ capping design and costing based on the ERC User Guide. In other words, the ERC User Guide—approach to capping mine waste storage facilities is informative rather than mandatory. Further, the ERC User Guide provides little guidance on the reprofiling and treatment of the side slopes of mine waste storage facilities.

7.1 Commentary on cover design

The ERC User Guide states that “the ‘default’ rates for rehabilitation of” WRDs, TSFs and heap leach pads “are based on the chemical and physical properties of the wastes”. The ERC User Guide interprets this to mean that ‘high risk’ applies if there is a presence of (any) PAF material, and also for TSFs higher than 30 m, requiring a high risk cap. The ‘encapsulation’ of PAF materials in the ground is what maintains them as PAF,

and PAF material could be effectively encapsulated and covered (as shown in Figure 3), minimising the risk that it would generate AMD.

The greatest proportion of PAF material may well be contained in the ore, if it is sulfidic, with some also in the 'halo' surrounding the orebody. The halo will report to a WRD or heap leach pad, while the tailings will report to a TSF. A small proportion of PAF waste rock can readily be encapsulated in a WRD, and/or the wetting up of the WRD can be limited, to limit the potential for the generation of AMD. Process chemicals often add ANC to the tailings, such as in gold processing using cyanide, delaying, reducing or removing the risk of AMD. Hence, the presence of any PAF material does not automatically dictate a high risk category.

The ERC User Guide does not specify cover designs for different climatic settings, nor the materials or placement to be applied in each of the layers defined. However, the climate, waste materials, and cover materials and their placement are key to the successful application of a cover and would likely impact its cost.

If a 'working layer' is required prior to capping tailings, it is to allow trafficking over soft tailings. Given that the tops of WRDs are trafficked, it is not clear why an additional working layer would be required. In the worst case of wet and soft tailings, a working layer may have to be applied hydraulically (by pumping coarse-grained material), or by end-dumping coarse-grained material from a stable tip head.

What is most important with a 'capillary break', if one is required, is the nature of the material used, which dictates the thickness required. Clean gravel would be suitable and would require a thickness of greater than 200 mm to remain effective as a barrier. Finding suitable material for an effective capillary break and ensuring its sustainability are problematic. The ERC User Guide makes no written mention of a 'double capillary break', or a 'two-layer capillary break', although DES does make mention of them in correspondence with operators.

A low permeability layer is the key defence against AMD, and what is important is the nature of the material used and its placement, rather than its thickness. An effective low permeability layer, particularly if it remains unsaturated, both limits the net percolation of rainfall into potentially contaminating wastes and the potential uptake of salts and contaminants into the overlying growth medium, rendering a capillary break unnecessary.

A low permeability layer could comprise compacted clayey material, but also compacted waste rock or, for tailings, a hardpan or compacted tailings could provide a low permeability layer. Further, a high-density polyethylene (HDPE) or low-density polyethylene (LDPE; providing greater strain capacity than HDPE) or GCL, with or without a compacted layer, could be suitable. A thin HDPE, LDPE or GCL may require drainage to minimise the potential head of infiltrated rainfall acting on it, and hence minimise net percolation through the liner. Otherwise, a composite liner including a geomembrane overlying a layer of compacted clay may be required.

The 'top rock layer' is presumably part of the growth medium and should be placed loose to promote rainfall infiltration and storage, with the topsoil ripped in, to promote the establishment and sustainability of revegetation.

The 'default' growth medium thickness is 0.15 m in all cases. In many parts of Queensland, the natural topsoil is very limited in thickness or even non-existent. Loosely placed weathered NAF waste rock may be a suitable growth medium with minimal or no topsoil and would limit rainfall runoff and erosion much more than bare or poorly vegetated topsoil, particularly on slopes. If topsoil is applied, it should be ripped into the top rock layer to maximise its effectiveness, while minimising erosion.

Although no capping is specified by the ERC User Guide for 'very low risk' waste facilities, revegetation may require nutrient or topsoil addition.

7.2 Commentary on cover design appropriate to dry regions of Queensland

For semi-arid or seasonally dry climates in Queensland, a store and release cover is appropriate for sulfidic waste rock (and heap leach material), and tailings, typically comprising a nominal 0.5 m thick low

permeability layer overlain by a loose 1.5 to 2 m thick rocky soil mulch growth medium, giving a total thickness for this relatively simple two-layer cover of 2 to 2.5 m. Attention should focus on climatic extremes, the waste materials, and the design, materials selection, and the construction of such store and release covers to ensure that they restrict the net percolation of rainfall where AMD may occur.

Experience at Kidston Gold Mines indicates that store and release covers on the top of the WRD have restricted net percolation to less than 1% of mean annual rainfall, and have achieved good revegetation of eucalypts, acacias and grasses sufficient to control erosion (Williams et al. 2022).

Store and release covers should not shed rainfall, to avoid erosion loss. Alternatively, PAF material could be encapsulated or submerged permanently below water in completed pits, provided that they remain groundwater 'sinks'.

The possible requirement for a 'double capillary break' in semi-arid regions of Queensland is questioned; it is not specified in the ERC User Guide and is not appropriate for dry climatic settings. The only place it has been applied was for the specific purpose of increasing the infiltration and net percolation of rainfall in a net positive precipitation climate.

7.3 Commentary on slope reprofiling and treatment, and surface drainage

The ERC User Guide does not specify the slope angle for the side slopes of WRDs, heap leach pads or TSFs, but presumes 'reprofiling', which forms the basis for calculating costs. For a given slope height, slope flattening increases the length of the slope and generates a smoother surface texture due to the crushing and burial of coarse-grained particles, and hence increases runoff and erosion. Leaving angle of repose NAF WRD slopes is not considered, despite it being applied at a number of sites in Queensland (including at Kidston and Century mines, where it has performed well), and performing far better in terms of limiting erosion and promoting revegetation than reprofiled WRD slopes (such as at Mt Leyshon Mine).

Slope flattening should be a choice between leaving slopes at angle of repose, flattening slopes by dozing to half the angle of repose or flatter (which is the steepest slope that can be constructed), and constructing concave slope profiles by dozing lower benches to mimic natural slope profiles. The choice should depend on the surrounding hillslopes, the slope materials and their erodibility, the desired and sustainable revegetation, community rehabilitation goals, and the post-mining land use or ecological function. A range of slope treatment options may best mimic variable natural hillslopes.

Topsoil and/or weathered rock could also be end-dumped over angle of repose NAF waste rock slopes to ravel downslope and wash into the waste rock, and then fertilised and seeded aerially (as was practised at Kidston Gold Mines, where it performed well, and far better than slope flattening and capping with weathered material; Williams et al. 2022).

The ERC User Guide states that "drainage is typically required on the finished cap to ensure that surface water drains off the cap". The provision of top drains, and contour and downslope drains, on mine waste storage facilities concentrates rainfall runoff and cannot be accommodated in design, as has been demonstrated at mines throughout Queensland and elsewhere and is not recommended. Further, unless slopes can be sufficiently well revegetated to control erosion, they require surface texture for erosion control.

8 Conclusion

The Queensland Estimated Rehabilitation Cost User Guide (ERC User Guide) provides guidance on cover layers and their thicknesses for the risk category assigned to stored mine wastes. The prime purpose of the capping of mine waste storage facilities is to minimise the potential for environmental harm, informed by expert opinion, rather than adopting a 'default' capping design and costing based on the ERC User Guide.

The ERC User Guide does not specify cover designs for different climatic settings, nor the materials or placement to be applied in each of the layers defined. However, the climate, waste materials, and cover materials and their placement are key to the successful application of a cover and would likely affect its cost.

For semi-arid or seasonally dry climates in Queensland, a store and release cover is appropriate for sulfidic waste rock (and heap leach material), and tailings, typically comprising a nominal 0.5 m thick low permeability layer and a 1.5 to 2 m thick growth medium, giving a total thickness for this relatively simple two-layer cover of 2 to 2.5 m. Attention should focus on climatic extremes, the waste materials, and the design, materials selection, and construction of such store and release covers, to ensure that they restrict the net percolation of rainfall where AMD may occur.

The ERC User Guide does not specify the slope angle for the side slopes of WRDs, heap leach pads or TSFs, but presumes 'reprofiling', which forms the basis for calculating costs. For a given slope height, slope flattening increases the length of the slope and generates a smoother surface texture due to the crushing and burial of coarse-grained particles, and hence increases runoff and erosion. Leaving angle of repose NAF WRD slopes is not considered, despite it being applied at a number of sites in Queensland and performing far better than reprofiled WRD slopes.

References

- Agnew, MK 1998, *The Formation of Hardpans Within Tailings as Possible Inhibitors of Acid Mine Drainage, Contaminant Release and Dusting*, PhD thesis, The University of Adelaide, Adelaide.
- Bussière, B, Maqsoud, A, Aubertin, M, Martschuk, J, McMullen, J & Julien, M 2006, 'Performance of the oxygen limiting cover at the LTA site, Malartic, Québec', *CIM Magazine*, vol. 1, no. 6, pp. 1–11.
- Bussière, B, Potvin, R, Dagenais, A-M, Aubertin, M, Maqsoud, A & Cyr, J 2015, 'Restauration du site minier Lorraine, Latulipe, Québec: Résultats de 10 ans de suivi' (Restoration of the Lorraine mine site, Latulipe, Quebec: Results of 10 years of follow-up), *Sciences & Techniques*, vol. 54, pp. 49–64.
- CIPEC 2005, *Benchmarking the Energy Consumption of Canadian Open-Pit Mines*, Mining Association of Canada and Natural Resources Canada, Ottawa.
- Davies, MP & Rice, S 2001, 'An alternative to conventional tailing management: "dry stack" filtered tailings', *Proceedings of Tailings and Mine Waste 2001 Conference*, A.A. Balkema, Amsterdam, pp. 411–422.
- Department of Environment and Science 2019, *User Guide for Estimated Rehabilitation Cost Calculator for Mining, Operational Support*, Department of Environment and Science, Brisbane, https://environment.des.qld.gov.au/__data/assets/pdf_file/0029/89615/rs-gl-user-guide-erc-calculator-mining.pdf
- DMIRS 2020, *Statutory Guidelines and Mine Closure Plans*, Department of Mines, Industry Regulation and Safety, Government of Western Australia, Perth, <http://www.dmp.wa.gov.au/Environment/Mine-Closure-Plan-6034.aspx>
- International Network for Acid Prevention 2009, *Global Acid Rock Drainage Guide*, INAP, Brisbane, <https://www.gardguide.com>
- Land Court of Queensland 2021, *Century Mining Limited v Department of Environment and Science [2021] QLC 3*, <https://archive.sclqld.org.au/qjudgment/2021/QLC21-003.pdf>
- Smirnova, E, Bussière, B, Tremblay, F & Bergeron, Y 2011, 'Vegetation succession and impacts of bio-intrusion on covers used to limit acid mine drainage', *Journal of Environmental Quality*, vol. 40, no. 1, pp. 133–143.
- So, HB, Sheridan, GJ, Loch, RJ, Carroll, C, Willgoose, G, Short, M & Grabski, A 1998, 'Post-mining landscape parameters for erosion and water quality control', *Final Report on ACARP Projects C1629 and C4011*.
- Williams, DJ 2006, 'Mine Closure as a Driver for Waste Rock Dump Construction', in AB Fourie & M Tibbett (eds), *Mine Closure 2006: Proceedings of the First International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 697–706, https://doi.org/10.36487/ACG_repo/605_61
- Williams, DJ 2014, 'Mine planning for the final landform', *Proceedings of Fifth International Mining and Industrial Waste Management Conference*, SAICE, Rustenburg, p. 52.
- Williams, DJ 2019, 'Obstacles to effective mine closure, rehabilitation and relinquishment', *Proceedings of Tailings and Mine Waste 2019 Conference*, Vancouver, pp. 1271–1286.
- Williams, DJ 2020, 'Geochemical and Hydrological Lags and Impact on Covers on PAG Mine Wastes', *Proceedings of Tailings and Mine Waste 2020*, pp. 505–518.
- Williams, DJ, McGhie, A & Short, T 2022, 'Repurposing of the Genex Kidston mine site in Queensland, Australia', in M Tibbett, AB Fourie & G Boggs (eds), *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 789–802.
- Williams, DJ, Wilson, GW & Currey, NA 1997, 'A cover system for a potentially acid forming waste rock dump in a dry climate', *Proceedings of Tailings and Mine Waste 1997 Conference*, Fort Collins, pp. 231–235.
- Zhang, C, Williams, DJ, Lei, X, Zhu, Y & O'Neill, M 2018, 'Instrumented column testing of salt uptake from compacted red mud into a cover', *Proceedings of Mine Waste and Tailings Stewardship Conference 2018*, Brisbane, pp. 220–227.