Mine Closure 2016 – AB Fourie and M Tibbett (eds)

doi:10.36487/ACG_rep/1608_47_Wright

A common-sense approach to mine closure design in the remote Western Australian interior

A Wright *MBS Environmental, Australia*

Abstract

In recent years Western Australia has seen a far greater focus on mine closure planning, with both the Government and the Mining Industry tackling implementation of rather conceptual mine closure strategies that are set early in the mine life. Both practitioners and Government stakeholders have the best of intentions when setting mine closure objectives, standards and completion criteria, but just how realistic are these when it comes to implementation?

This paper looks at what might be considered both pragmatic (cost-effective and achievable) and responsible with regard to mine closure in the arid WA Goldfields region. It draws on twenty years of keen observation of the successes and failures of mining industry efforts in this region and recent scientific findings by several local consultants. The focus is on closure design of those mine landforms that remain post-closure — mine pits, waste rock dumps, stockpiles, leach pads and tailings storage facilities. It examines the actual set of field conditions under which mines operate, post-closure modelling time frames and research (and predicative modelling) limitations. The paper suggests where closure design efforts should be focused and how best we might interpret the current WA Government mine closure guidelines. It identifies several closure design aspects that remain misunderstood by many stakeholders, resulting in unrealistic expectations and closure criteria.

1 Introduction

Mine closure planning appears to have come of age in Western Australia (WA) with the regulatory requirement for Mine Closure Plans and establishment of auditable closure cost estimates. The concept of mine closure is no longer an unfamiliar concept to most mine operators and for many it is now a harsh reality, thanks to the recent economic downturn. There is a far greater awareness that mines do not go on forever and that it is generally market forces, rather than resource depletion, that shut down operations. This is particularly true for the metalliferous mines located within the WA Yilgarn Craton (Figure 1) where mineralisation generally extends to depths well below current mining levels. At the end of the day mining by its very definition ‘the extraction of a finite ore from the earth’ is not sustainable over time and will result in a residual footprint on the land. The process of mine closure planning has been well established in WA for some time as is borne out by this, the 11th International Mine Closure Conference hosted by the Australian Centre for Geomechanics.

The release and implementation of the 2011 Department of Mines and Petroleum (DMP) *Guidelines for the Preparation of Mine Closure Plans* played a major role in kick-starting the process across the entire WA mining industry. Whereas previously only the larger mining companies tended to have comprehensive mine closure plans and mine closure provisions that met international norms and standards, this has now been imposed across the entire WA mining industry. In May 2015, the DMP issued an updated version of the Guidelines based on lessons learnt over the past three years. Unfortunately, while much progress has been made, the guideline document is still interpreted by many within government as a reporting template/format to be strictly adhered to rather than a guidance document. While this may make for ease of regulatory control it unfortunately tends to stifle innovation and pursuit of many of the principles behind effective mine closure planning. A ‘one size fits all’ highly prescriptive reporting format is not in the best interests of the mining industry.

Figure 1 Location of Yilgarn Craton region within Western Australia

An additional driver for raising awareness in mine closure planning has been the introduction of the Mining Rehabilitation Fund (MRF) Levy in WA. This has had a profound impact across the local mining industry with the smaller operators no longer saddled with mining bonds and the large multi-nationals now for the first time having to pay 'real' money to the Government. The flipside of the coin, however, is that for the first time the DMP has a true rehabilitation war chest and will now have to actually 'walk the talk'. The levy is a very effective tool for not only encouraging progressive rehabilitation, but also more accurate closure cost estimation which in turn requires formulation of realistic closure designs and strategies. Once again it has taken the forced expenditure of money to move industry beyond just the documentation of motherhood-like statements in the mine closure plan (MCP). So what can we realistically hope to achieve with closure strategies and engineering designs in the Yilgarn Craton region of the WA outback?

2 Government expectations

The WA Government by virtue of its role as both regulator and custodian of the land (in reality the ultimate land owner) is the primary stakeholder who determines what will be accepted for mine completion (mining lease relinquishment). The two key government agencies dealing with mines in WA are the DMP and the Environmental Protection Authority (EPA) with the former acting as the lead agency. The DMP 2015 Guidelines for the Preparation of Mine Closure Plans (DMP 2015), a joint development by the two government agencies, provides the following direction:

- The DMP principal closure objectives are for "rehabilitated mines to be (physically) safe to humans and animals, (geo-technically) stable, (geo-chemically) non-polluting/non-contaminating, and capable of sustaining an agreed post-mining land use".
- The EPA objective for Rehabilitation and Decommissioning is "to ensure that premises are decommissioned and rehabilitated in an ecologically sustainable manner".

The issue then for the closure planning team is to establish closure criteria for the above objectives. When examining mine landforms what do we consider as safe, geotechnically stable, and non-polluting? Also, what is a realistic timeframe against which to judge sustainability trends?

We do, however, have to remember that the sole purpose of a privately listed mining company is to make money for shareholders and as such, once mining ceases and the income stream dries up, the basic requirement is a timely exit. While companies strive to do this in a responsible manner, they also need to do it in a timely and cost-effective way. The Government in turn, as the ultimate custodian of the land, wants to ensure that it is not left with a legacy mine site with ongoing rehabilitation expense. Clearly the path forward involves cooperation and sharing of ideas between the two parties in order to get final agreement on what is generally a compromise closure strategy. Both parties have to be pragmatic otherwise one will be left with an unwanted 'lemon' and history tells us this is generally the State. The DMP database currently records some 17,000 abandoned mine sites in Western Australia. While most of these are small historic workings, a good many represent unacceptable scars on the landscape with significant safety issues.

3 The reality of mining

The remote nature of many mine sites and local climatic conditions of the Yilgarn Craton have a significant bearing on closure designs and rehabilitation strategies. Unlike the wetter regions of the country it is generally not possible to hide any past mining activity with vegetation. The low and erratic rainfall (Figure 2) received over much of this region not only means that vegetation growth is severely handicapped, but also that natural processes of erosion, both physical and chemical, take far longer than in the better watered regions of the country.

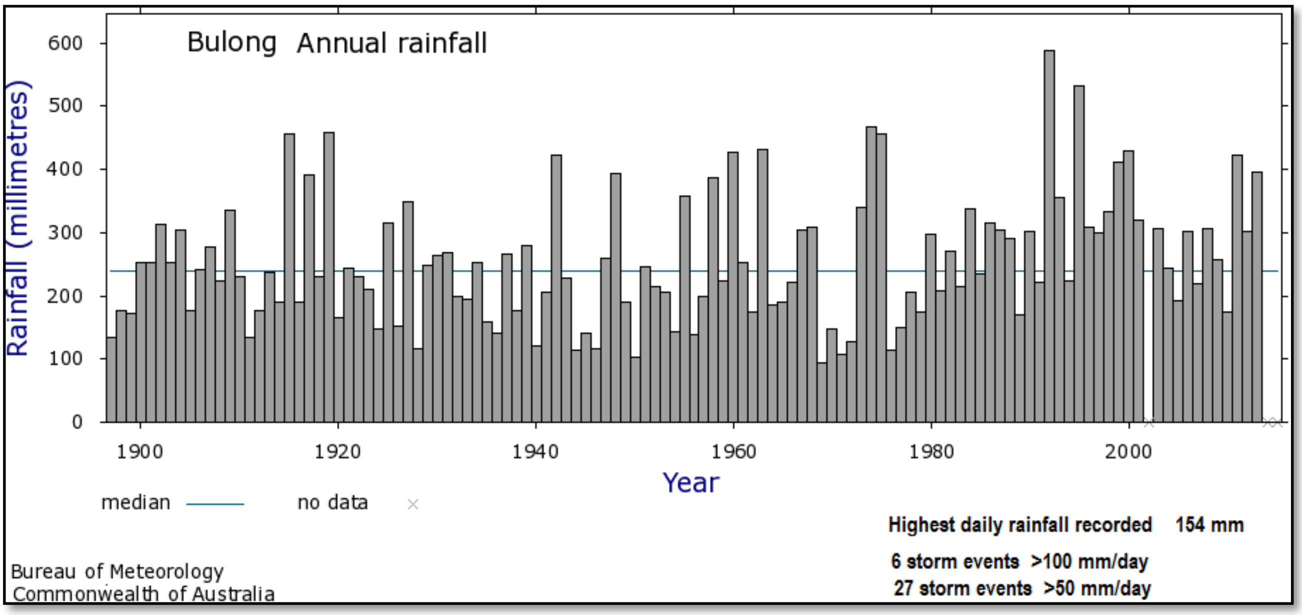

Figure 2 Typical annual rainfall trend in Eastern Goldfields (BoM 2015)

The arid nature of the region has significant implications for closure planning both in regard to engineering design and rehabilitation strategies. Annual rainfall figures are useful in illustrating climatic trends over time and well defined wet and dry cycles that impact on vegetation regrowth, but little more (Figure 2). It is the rainfall pattern and intensity of individual storms that is of greater importance for closure design. Most precipitation is received as short intense thunderstorms or distinct rainfall events linked to the tail of cyclonic systems moving down from the northwest coast. In wet cycles the region can receive two or three such cyclonic systems in a year with an extreme event at least once a decade. Such storm events may result in half the annual total rainfall in a single day causing severe flooding of the countryside (see Figure 2 text).

Closure drainage designs need to be engineered to these high intensity storms rather than the low average annual rainfall.

Recorded rainfall records seldom exceed more than 125 years but do show distinct wet and dry cycles. Drought periods may extend for several years and below average rainfall conditions for up to twenty-year cycles. This clearly has significant ramifications for vegetation growth, particularly shrubs and grasses, as only the hardiest of species tend to survive the harsher dry cycles particularly when these extend over long periods. The reality of climate change is that these extremes are just going to become more accentuated. Mine closure planning is now expected to include consideration of possible climate change so what does this mean in practice? The answer is, plan for the extreme, take a conservative engineering approach — double the length of currently recorded drought periods and design to probable maximum precipitation (PMP).

An engineering design aspect that is commonly misunderstood is that of hydrological probability. For operational purposes, engineering structures are commonly designed to meet the 1-in-10 year 24 hour storm event and the 1-in-100 year 72 hour storm event. This is based on an operational life ranging from 20 to 50 years. In the case of closure planning we have to design to a potential 1,000 year time frame. The DMP guidelines use an arbitrary +300 year post-closure time frame to give some substance to this extended time frame. To put this in to context, a structure engineered to meet the 1:100 year 72 hour criteria will after fifty years have a greater than 65% probability of failure. These odds of failure increase dramatically as the years pass so that in reality one has designed the structure to fail well within the hoped for life span (+300 year target) of engineering structure.

The local climate and geology have a profound effect on the materials that we need to use during closure. Unlike many other regions of the world, WA rangeland soils are extremely old and infertile as a result of hundreds of thousands of years of weathering. The soils in upland areas are generally thin having been depleted by wind erosion, sheetwash erosion, and leaching of the nutrients and minerals by chemical weathering. The result is the accumulation of silts, clays and salts in the broad almost indistinct internally draining paleochannel valleys. The surrounding natural landforms have similarly formed over hundreds of thousands of years of physical and chemical erosion. Ridges and plateaus that remain elevated above the relatively flat plains invariably owe their existence to the presence of more resistant geological formations. While under normal circumstance these landforms are stable and in natural equilibrium, during extreme storm conditions the forces of erosion remain as active as ever continuing to generate gullies and alluvial fans on the edge of the surrounding plains. Many stakeholders tend to forget that the environment in which we find ourselves has formed over many thousands of centuries and continues to change all the time. It is unrealistic to think humans can achieve in a matter of years what nature has taken an eternity to do. That is, based on a responsible budget.

The exceptional depth of in situ weathering means that many mine pits intersect highly oxidised geology down to considerable depth with fresh rock only encountered at depths of 50 to 80 m below surface. This may make for easy digging but has significant consequences for final pit wall stability and physical stability of mine waste landforms. Freshly exposed pit walls erode easily and, if not regularly maintained, result in dramatic slumping and wall collapse (Figure 3). Mine waste material removed from the pit and used to construct the waste rock dumps generally has limited physical structure being both dispersive and sodic in nature. The result is mine landforms that are inherently unstable, both physically and chemically, and require engineered landform covers. With many mines not extending down into fresh rock closure teams often lack a source of competent rock with which to work, coupled with mine waste material that is hostile to vegetation growth. These mine waste landforms continue to erode, discharging large volumes of sediment onto the surrounding environment, a completely natural geomorphological process, but one unacceptable to Government stakeholders (Figure 4).

Figure 3 Typical Eastern Goldfields 'palaeochannel' mine pit

Figure 4 Actively eroding gullies in a mine waste rock dump

Finally, the hydrological environment in which the mine is located differs profoundly from that found elsewhere in the State. So closure criteria applicable to the better watered northern mining regions of WA should not be applied to the Yilgarn Craton region. The region does not have permanent surface water resources with creeks only flowing very briefly during and immediately after rainfall events. Rapid runoff in the form of sheet flow is the dominant hydrological process and concentrates as channel flow in large inward draining paleodrainage systems. These systems ultimately feed into large depressions (saline lakes) that act as hydrological sinks and natural salt concentrators. It is only in the Murchison region that creek flow discharges into rivers that reach the coast and constitute important fresh water systems. Where river pools persist for any length of time after rainfall events these are groundwater-dependent and seasonal in nature. Groundwater serves as the main source of water supply in the region, however, aquifers remain highly localised and of limited value due to the general saline nature of the water. Most shallow groundwater is brackish with freshwater generally limited to unconfined alluvial aquifers and shallow calcrete/silcrete units. The deeper bedrock formations host fractured rock aquifers that are seldom hydrogeologically connected. Where these fractured zones contain mineralisation and constitute orebody aquifers, the groundwater is likely to have slightly raised concentrations of a number of elements that might impact on potential water usage. Groundwater within the paleochannels, which are often higher yielding aquifers, is generally hypersaline (salinity levels well in excess of 200,000 mg/L TDS) and hence of limited use outside of the mining industry. Those local aquifers that do provide fresh to brackish water are considered important water resources by both miners and farmers.

The vast majority of the mines in the arid WA interior are far removed from population centres and towns. It might be argued that many mines are little more than a speck on the landscape and, when considered in a regional context, tend to be rather insignificant. Once all mine infrastructure is removed from a site all that is left is the mine pit(s), unseen underground cavities in the case of underground mines, and mine waste storage landforms such as waste rock dumps (WRD), tailings storage facilities (TSF), low grade ore stockpiles, and heap leach pads (HLP). While these mine landforms can be designed to be relatively stable, they will all continue to erode over time as Mother Nature takes control and over thousands of years establishes a new geomorphologically stable landscape. The isolated nature of most mines also means that post-closure land use options are fairly limited. Most mine sites are invariably going to revert to, at best, low intensity grazing land with the caveat that they remain prospective for mineral exploration. All other land reverts to Crown Land, either as managed ‘nature’ reserve or vacant land. While stakeholders often like to suggest fanciful post-closure landuses it is in reality difficult to make a realistic business case for such ventures. A case could possibly be made for some form of ecotourism and/or historic mine heritage trail where these sites are in close proximity to established transport routes (highways and outback touring tracks), but mine planners need to take care not to be sucked into fanciful promises and unrealistic commitments during the initial project approvals phase.

4 An interpretation of closure objectives

Based on the above general points, what can we realistically hope to achieve when rehabilitating the various mine landforms. Firstly, it is recognising that the ‘one size fits all’ approach is not wise. While a degree of rationalisation is possible, regional and site specific conditions have to be taken into consideration. The DMP guidelines have been written to cover the entire state and many of the closure prescriptions are geared towards mines in the better watered Pilbara and Kimberley regions and more populated coastal region. Secondly, the process of mine closure must have a realistic completion date and stakeholders have to accept that miners do not have unlimited budgets. While many mining companies attempt to have conservative closure provisions these are seldom able to cover all possible engineering closure design options. The result is that closure strategies, while based on industry best practice at the time of design, have to be cost-effective and realistic to ensure the long-term sustainability of the mining industry. A far too common comment heard at mine sites is ‘we would never have built the damn thing if we had known that’s what it would cost to close’. Rehabilitation performance monitoring periods have to be realistic and closure criteria linked to the establishment of recovery trends and not necessarily full recovery.

We should, based on a risk approach, focus on two key areas when considering post-closure mine landforms:

- Safety — that is during closure activities and post-closure.
- Impacts on the environment — that is the potential impact that post-closure mine landforms might have on the surrounding environment.

Other aspects while important should not be considered paramount for gauging final success in mine closure. The desire by some stakeholders to persevere with concepts such as ‘zero environmental impact’, ‘full environmental recovery’, ‘enhanced post-mining landuse’, and ‘risk free relinquishment’ are not appropriate for the Yilgarn Craton mine sites given the remoteness and climatic conditions.

4.1 Safety aspects

Safety during closure activities is paramount and constitutes a natural extension of existing operational site procedures. Where possible, uncertainty creeps in as with safety during the post-closure period. This basically relates to the safety of people accessing the site and post-closure mine landforms either officially or unofficially. What can we realistically do to leave a safe environment, knowing the inquisitive nature of humans? The answer is implementation of engineered closure designs that meet current industry best practice. It is physically possible to restrict all human access to any underground workings, however, with above ground mine landforms all that is possible is to restrict unintentional vehicle access to any potentially unsafe areas.

Open cut mine pits are the obvious high risk landform which we know are going to remain geotechnically unstable for hundreds if not thousands of years to come, particularly if the pit walls are not hard rock (Figure 2). The most practical closure strategy therefore is to restrict vehicle access by:

- Ensuring that the mine pit abandonment bund is correctly located beyond what might be considered the long term instability zone. This zone is best defined by the site geotech engineers (or geologists) as they fully understand the local geological conditions. The default methodology is that recommended by DMP guidelines (DoIR 1997). It is best if using this DMP 'rule of thumb' methodology (Figure 5) to have the final location validated by an appropriately qualified person.

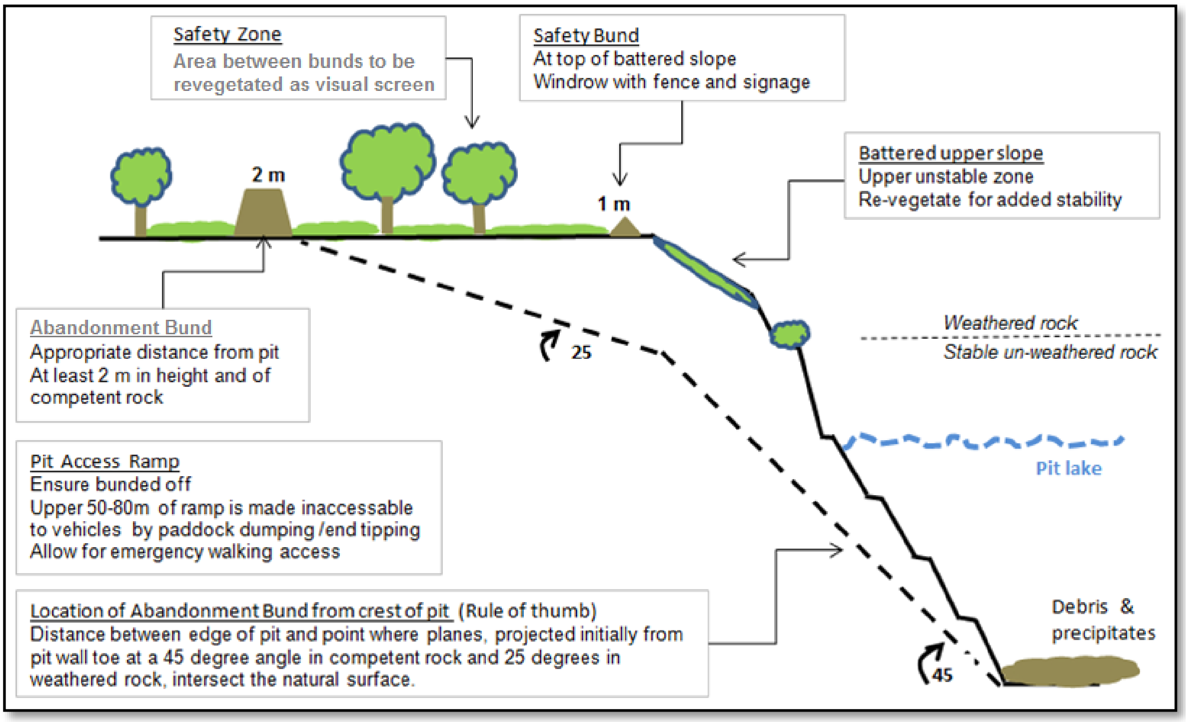

Figure 5 Mine pit closure strategy based on DoIR (1997)

- It is important that this exercise be undertaken during the mine planning phase to avoid the placement of other mine landforms within the final pit instability zone. The practice of mine planners placing mine waste rock dumps as close to the mine pit as possible to reduce haulage distance (and costs) has serious closure ramifications. Unfortunately the closure team is more often than not faced with a *fait accompli* where the mine waste landform such as a waste rock dump or tailings storage facility (TSF) has already been built within what is considered the pit instability zone. There is clearly a danger that over time a portion of these landforms may collapse into the mine pit leaving unstable, angle of repose final waste dump slopes. In this case the common practice of keying the pit abandonment bund into the toe of the mine waste landform is not acceptable. Any unsuspecting person approaching the unstable batter from the far side of the waste landform would be unaware of the safety risk of this dump slope on the very edge of the mine pit. The extension of the pit abandonment bund around the toe of the entire mine waste landform, while more costly, does mitigate the risk. An additional benefit of such a WRD toe bund is that it doubles as a sediment retention structure ensuring additional insurance against any sediment discharge from the waste rock landform, should any cover design fail resulting in excessive erosion. The bunds also serve to discourage unnecessary vehicle access to the landform and in so doing avoiding unintentional interference with rehabilitation measures such as vegetation regrowth and erosion control. With mine landforms constructed out of highly dispersive material it only takes one set of tyre or dozer tracks vertically up the slope to initiate gully erosion.

- The material used to construct the abandonment bund is also important as it determines the long term integrity of a structure that is expected to remain functional for hundreds of years. Where oxide material or weathered sediments are used the cross-sectional area of the bund needs to be increased significantly. Appropriate technical advice needs to be sought regarding the physical strength of the chosen construction material and its ability to withstand general storm induced erosion over time. As a rule of thumb, if using oxide mine waste material the bund should be at least 2.5 m high with an upper width of no less than 2.5 m.
- An additional safety measure is the retention of the operational safety windrow and blocking-off of the pit ramp to restrict any vehicle access. The pit access ramp is often kept open throughout the rehabilitation performance monitoring period with access control achieved by means of a fence and padlocked gate. Ultimately, however, it is wise to block off the upper portion of the access ramp by paddock dumping over the first 8 to 10 m of ramp at the very pit crest. This effectively serves to restrict vehicle access, only permitting emergency access by foot.

These measures are all relatively easy to implement and abandonment bunds are best done before the mining fleet is removed from the pit. Many of the goldfields mine pits stop at the fresh rock interface and a final hard rock blast/dig should be considered to provide a source of suitable reclamation material. Remobilising mine fleets or having to establish new borrow pits post mining is a more costly exercise. There are clear financial benefits in early construction of abandonment bunds as progressive reclamation works help reduce annual MRF Levy payments.

Dealing with an underground mine (workings) is relatively simple as once all salvageable equipment and plant has been removed the closure team literally ‘closes the door’ to deny any further access. The sealing of all openings – portals, shafts, declines, adits and vents – is a straightforward task and should occur at all access points, whether these are likely to be below the pit lake water level or not. This should include any known historic shafts that pre-date the modern mining activity but connect to current underground workings. There is a corporate responsibility to leave adequate mine plans showing all areas underlain by relatively shallow underground voids as these could possibly over time result in some degree of subsidence or gradual collapse. The geotechnical evaluation as to whether any of these areas pose a potential risk of sinkhole development needs to be done by a suitably qualified professional as this does pose a real safety risk and requires implementation of precautionary mitigation measures.

Safety concerns at other mine landforms generally relate to operator safety during closure activities. The slope angle at which machines may work to accomplish the proposed closure task is routinely managed in operational safety plans. Compliance with the standard DMP ‘20° slope angle’ rule is now generally accepted by industry and represents common sense, rather than any scientifically based guidance. A safety factor does, however, creep in when closure planners interpret this to mean the overall slope angle of the entire batter from toe to crest (a common practice at TSFs). This interpretation does mean sections of the outer profile could be extremely steep and unsafe for wheeled vehicles. A situation that is commonly observed at many of the older mine landforms that have been rehabilitated during earlier eras. This practice can often result in later difficulties when maintenance/repair work needs to be done to the rehabilitated batters. Figure 6 shows one such problematic batter where the slope angle is in excess of 28° and too steep for even tracked machines.

Figure 6 Over steep mine waste landform batters requiring repair

4.2 Environmental impacts

The geotechnical and geochemical stability of the post-closure mine landforms largely determines how big a risk it poses to the surrounding environment. The objective of the closure team is to as best possible eliminate any risk or at least contain any impact to the immediate footprint of the landform. The aim should be to safeguard against loss of any potential water resources or impact on any proposed post mining landuse. This recognises that erosion is a natural process that will occur any time a landform is not in equilibrium.

In the case of mine pits the main area of concern is the potential impact that mine pit lake may have on any adjacent aquifers and surface water bodies. The development of mine pit lakes receives considerable attention in the DMP 2015 Guidelines and has recently been mentioned as a key area of concern by the EPA (AMEC 2014 Mine Closure Conferences in Perth). This renewed regulator interest needs to be interpreted with some caution in a region like the WA Goldfields where the hypersaline nature of much of the water plays an important role in determining actual risk levels. In many cases, the mine pits can be shown to be hydrogeologically isolated from surrounding aquifers and surface water bodies, the pits themselves remain groundwater sinks and the high salinity levels in the pit lake nullify any water quality contamination concerns. The mining industry should not presuppose that they need to do sophisticated pit lake water balance models and hydrogeological assessments. While this may be the case in the better watered areas of the State where local freshwater resources are critical to environmental wellbeing, it is generally not the case in the more arid Goldfields region of WA. It is suggested that in most cases a simple conceptual hydrogeological evaluation and 'bathtub' like water balance suffices for closure planning purposes. The basic information required to do this is generally readily available at the mine and just needs to be drawn together into a simple conceptual model. Care needs to be taken not to over-complicate the issue. What is required is an understanding of:

- The orebody aquifer(s) and its potential linkage to adjacent aquifers.
- Whether local aquifers and surface water bodies realistically constitute what might be considered a water resource.
- Whether the final pit lake constitutes a groundwater sink or throughflow cell (intersects a palaeochannel).

- Whether there is any risk of the pit lake overtopping and spilling to the environment and if so, what risk this poses.

The need for predicting pit lake post-closure water quality trends in detail is only necessary if the pit lake water quality is such that it might be considered a future water resource. This is clearly not the case where pit lake water is going to be hypersaline (anything in excess of 35,000 mg/L TDS). There is generally no need for establishing a sophisticated hydrogeological water balance model for the underground mine as in reality all this represents is additional water storage capacity prolonging the mine pit lake groundwater recovery time.

With regard to mine landforms such as waste rock dumps, low grade ore stockpiles and TSFs, the concern relates to potential exposure of 'contaminants' on the outer surface and possible removal of this material either by wind or water to impact on surrounding water resources or land uses. The term 'contaminated material' here being used very loosely to cover actual chemical pollutants as well as fine grained highly dispersive sediment (tailings, oxidised waste material, silts and clays). The standard closure design strategy is based on: (a) encapsulation of any potential contaminated material; (b) construction of covers to mitigate against wind and water erosion; and (c) drainage management (seepage and runoff). Basic mistakes still seem to be made when formulating closure design strategies for the latter two aspects and the following discussion will focus on these.

The engineering and science related to encapsulation is generally well understood and implemented with most mines taking a very conservative design approach. The one area that still requires attention is that of engineered capillary breaks to counter the rise of salts to the landform surface through natural capillary rise. An issue that needs to be considered at most conventional paddock style tailings storage facilities. Industry has in the past often tended towards over-complicated cover designs that come at a significant cost. While such covers are critical in the better watered regions of Australia the same is not necessarily true for the arid WA Goldfields Region. Care should be taken to ensure that the design of the capillary break is appropriate for the given risk. Field and laboratory studies by Landloch (2015) suggest that in the Central Goldfields a 0.5 m thick cover of benign regrowth material is sufficient to hinder any rise of salts under normal climatic conditions. For much of the area mean monthly evaporation greatly exceeds mean monthly rainfall values for all months of the year with the ratio of monthly evaporation to rain always exceeding 3, with the ratio on an annual basis approaching 10 (Landloch 2015). As such, the near surface soils and mine wastes can be expected to be dry most of the time, only being moist for a short period after rain events. When evaporation demand is coupled with the potential for water to be extracted from near surface materials by vegetation, there is limited potential for percolation of incident rainfall into soils to any significant depth. A 25 mm rain event would be expected to wet only ~125 mm of the soil profile, and this water would largely be removed through soil evaporation. Interestingly, if rock is incorporated into a soil and comprises ~50% of the profile volume, the depth of wetting is predicted to essentially double and make such a profile less prone to water losses through soil evaporation. Field observation at numerous older mine sites indicates that frequently, when salts are exposed on the upper surface of mine waste landform it is due to either too thin a regrowth material cover or salts being drawn out of the cover material itself rather than from the mine waste pile below. In this case, the actual engineered capillary break layer has little to no influence on the observed outcome.

Industry as a whole is currently giving a good deal of attention to the design of covers on mine landform outer slopes (batters) and regulators expect to see scientific studies in support of any proposed cover design that may deviate from the age old re-vegetated topsoil approach. The result is a mining industry that is expending considerable time, effort and money on scientific studies and predictive computer modelling. A cynic might say consultants and researchers are rather good at selling the need for complex studies that invariably lead to sophisticated cover designs and detailed monitoring programmes. A simpler approach might be to just look at what nature has done over years. The gold mining industry in WA has been around for more than 120 years, resulting in thousands of mine waste landforms that now present us with actual trial studies on what does and doesn't work. Many of these mine landforms have been through numerous climatic cycles and physical processes have reached a level of maturity that suggest a new status quo (equilibrium).

One thing we know that does not work is vegetated soil covers. The sheeting of landforms with >200 mm of topsoil (or oxide mine waste) prior to deep contouring ripping and seeding does not provide long-term protection against raindrop erosion or concentrated surface runoff. Not only are many of the materials used as regrowth material (topsoil) basically infertile, but often actually hostile to plant growth. The leaching of salts from the material renders the covers hostile to most vegetation. Where seeds do germinate the newly vegetated areas are placed under immense stress by virtue of the irregular rainfall pattern and frequent long periods of drought (years). The extremely high evaporation rates throughout the year result in parched landscapes that are often also exposed to over grazing and bush fires. Figure 7 illustrates typical northeast Goldfields mine waste landforms that were once (20 years ago) considered 'successfully rehabilitated' yet are today considered a closure team's worst nightmare.

Figure 7 What remains of once-vegetated waste rock dumps some twenty years post-closure

Field evidence at numerous WA Goldfields minesites suggests that the most resilient slopes are those where the outer surface cover comprises a significant percentage of rock material (Figure 8). In their natural state hills and slopes in the Goldfields either have a protective rock capping/ledge or stony surface that has long been cleared of any loose fine grained soil (Figure 9). Final lower slopes are often comprised of a gritty/pebbly gravel surface with no more than scattered shrubs. Field studies by Landloch (2015) using a rainfall simulator in the central Goldfields indicated that a minimum 40% surface coverage is required to provide sufficient raindrop armouring to avoid uncontrolled erosion of the batters. Rock fragments as small as 1 cm appear effective against raindrop erosion. Ideally, however, the rock cover should comprise a range of rock sizes as illustrated in Figure 8. This rough surface retains the finer material and seeds between rock particles and boulders providing shade against the harsh summer sun resulting in greater soil moisture retention further boosting germination and vegetation growth.

Why do we still persist in sheeting surfaces with excessive thickness of topsoil (or any other available fine grained material) and then deep ripping the surface in an effort to restrict sheet flow and retain surface runoff for vegetation? Historic field evidence tells us that what this does is concentrate surface runoff within the irregular contour furrows resulting in tunnelling and overtopping and the generation of erosion rills and gullies (Figure 10). It is just a matter of time before much of fine topsoil material is removed en masse and we are left with bare eroded upper surfaces. The lateritic nature of much of the topsoil material does with time result in the formation of a thin outer skin that if not broken provides protection against wind erosion but not against concentrated (channelised) water flow (Figure 7). The erodability of soil covers appears to be influenced more by slope length than slope angle (McPhail & Rye 2008). Many upper slopes are seen to over time develop what appears to be a convex profile that suggests a form of slope creep has occurred on what might originally have been the steeper upper section of a designed concave slope profile. Figure 11 shows what can be achieved naturally when using the correct reclamation building blocks. This slope was not seeded and has experienced two normal rainfall seasons.

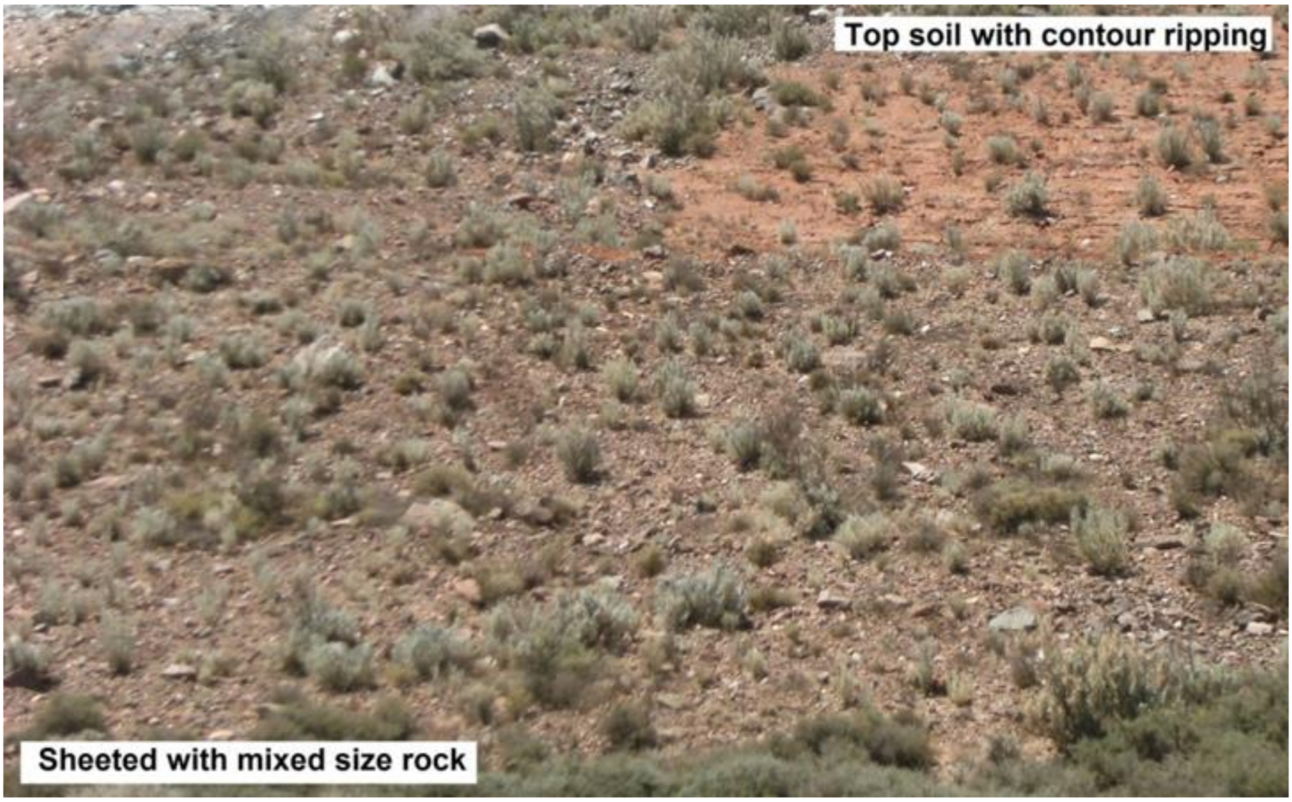

Figure 8 Rock covered outer slopes

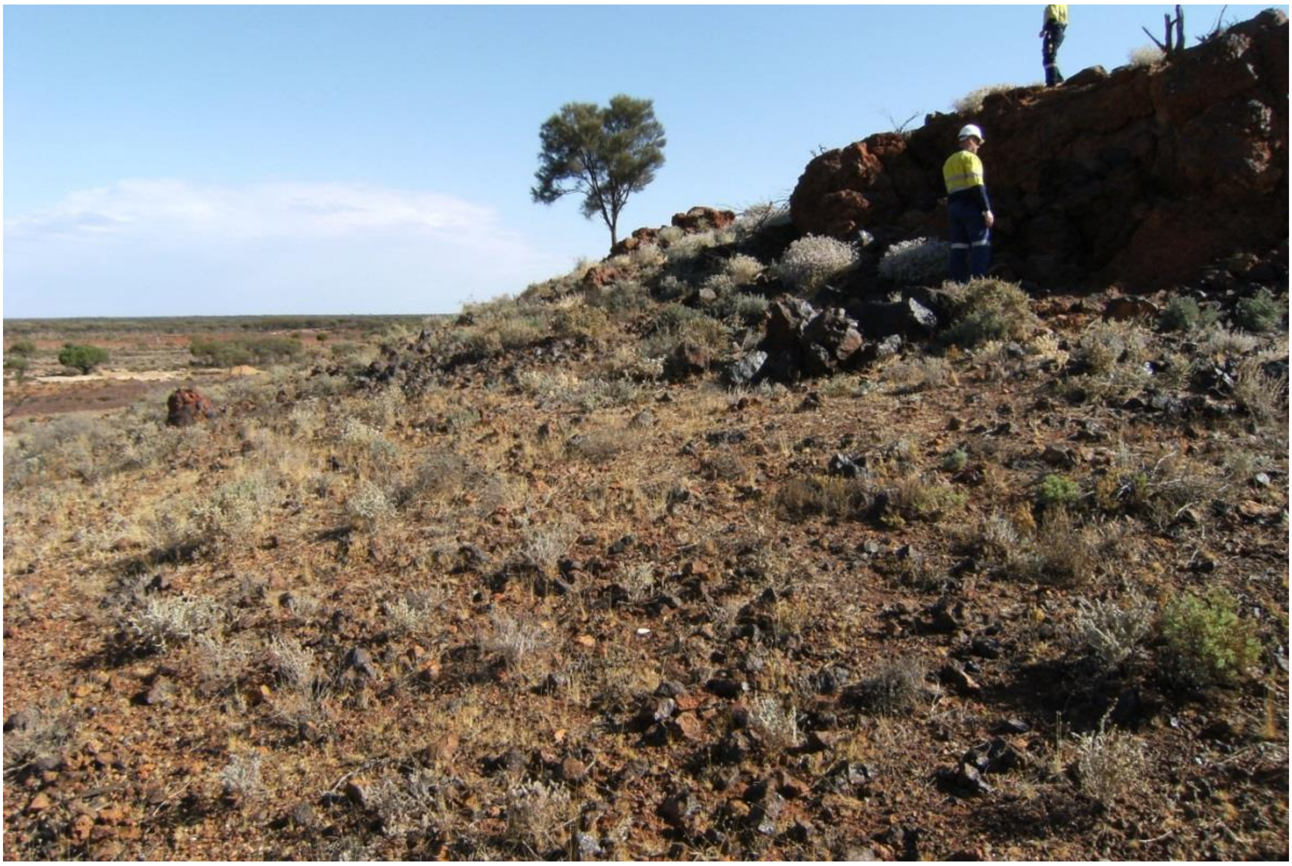

Figure 9 Natural hill slope in NE Goldfields region

Figure 10 Conventional topsoil cover deep-ripped along the contour

Figure 11 Unseeded rock mulch covers on 16° slopes

Field evidence suggests that the primary cause of cover erosion is surface drainage or storm runoff management on outer batters. It is the concentration of water either on the flat areas (dump tops or mid-slope berms) or within contour rips and drainage collection structures that poses the greatest risk. Where surface water runoff is allowed to pond behind crest bunds/windrows it commonly causes tunnelling or overtopping with the resultant concentrated surface flow having the power to erode the down-gradient cover material. Crest bunds and berm widths should be large enough to contain all storm runoff or, in the case of berms, removed during final reclamation works to provide a single slope profile. The general use of rock drop drains (chutes) to manage water off berms is highly problematic if these structures are not correctly designed and constructed by engineers. While these structures are commonly used on operationally active mine landforms such as TSFs where ongoing maintenance is regularly done, this is not feasible post-closure. Engineered closure structures need to be designed to be maintenance free structures and be able to safely convey runoff generated from PMP conditions.

5 Conclusion

Climatic and geological conditions in the Yilgarn Craton regions of WA have a significant influence on mine closure designs and strategies. Established rehabilitation strategies that rely on vegetation re-growth are not ideal for this region and prone to fail over the short to medium term. Rehabilitation recovery processes are likely to take decades, if not centuries, to establish a new equilibrium and this needs to be taken into consideration when establishing closure criteria. Similarly, consideration needs to be given to the saline/hypersaline nature of the receiving environment when evaluating the potential impact and risk that sediment and water discharges may pose.

Local conditions dictate that in the Yilgarn region closure planning focuses largely on (a) public safety and (b) how best to achieve geotechnical (physical) and geochemical stability of mine waste landforms over hundreds of years. This is best achieved through:

- Effective placement of abandonment bunds around mine pits and permanent sealing off of any openings to underground workings.
- Judicious use of rocky material when constructing mine waste landform covers. This should not necessarily be as rock amour, but rather poorly sorted ‘rock mulch’ which effectively over time naturally re-vegetates.
- Effective drainage control on mine waste landform outer batters through the use of competent rock crest bunds and removal of any narrow mid-slope berms.
- Greater use of sediment retention bunds along the toe of all mine waste landforms to serve as a not only a sediment control contingency measure, but also vehicle access deterrent.

Closure criteria applied in the better watered regions of WA should not automatically be applied to minesites located in the arid eastern interior of the State. Regulators need to remember that all closure planning is risk-based, with final rehabilitation performance based on confirmation of recovery trends rather than full environmental recovery.

References

AMEC 2014, Key note presentations by DMP and EPA, *Mine Closure & Rehabilitation Conference 2014*, Perth.

BoM (Bureau of Meteorology) 2015, Australian Government Bureau of Meteorology official website, http://www.bom.gov.au/climate/data/

DMP (Department of Mines and Petroleum) 2015, *Guidelines for Preparing Mine Closure Plans*, Western Australia Department of Mines and Petroleum and Environmental Protection Authority, May 2015.

DoIR (Department of Industry and Resources) 1997, *Safety Bund Walls Around Abandoned Open Pit Mines*, WA Department of Industry and Resources, Perth.

Landloch 2015, ‘Erosion Studies for a Tailings Storage Facility in the WA Eastern Goldfields’, technical report in *KCGM 2015 Mine Closure Plan*.

McPhail, GI & Rye, C 2008, ‘Comparison of the erosional performance of alternative slope geometries’, *ACG Rock Dumps 2008 Conference Proceedings*, Perth.