Final Report Project 3.5

A systematic and systemic review of mined landform stability and its impact on transitioning for regional benefits

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CRC TiME Transformations in Mining Economies

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Transformations in Mining Economies

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We acknowledge the traditional custodians across all the lands on which we live and wok, and we pay our respects to Elders both past and present.

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Executive Summary

This is the Final Report for the Cooperative Research Centre for Transformations in Mining Economies (CRC TiME) Project 3.5 entitled ‘A systematic and systemic review of mined landform stability and its impact on transitioning for regional benefits’. The project involved a systematic and systemic review of available Australian case studies of post-mining landform stability and their impact on transitioning the mine sites for regional benefits. The key aim of the project was to assess the geotechnical, erosional and geochemical stability, and acceptability for closure and post-closure land use and/or ecological function, of past and current mined landforms, to inform suitable future final mined landforms for a range of Australian mine site settings and mineral commodities. The dominant mine site settings are climate, topography and seismicity, although the Global Industry Standard on Tailings Management (GISTM, 2020) has added others. These include affected communities, management and governance (including environmental, social and governance known as ESG), emergency response and long-term recovery, and public disclosure and access to information.

The range of mineral commodities considered in the project included bulk commodities such as coal and iron ore, precious and base metals, and metals processed from oxide ores, and the associated open pits, overburden and waste rock dumps, underground workings, and tailings storage facilities.

The project involved a literature search and input from the experiences of the project research and industry end-user teams, on the performance of past and current mined landforms, covering a range of Australian mine site settings and mineral commodities. The mine site case studies considered showed effective mined landform design, construction and sustainability in the Australian context, for regional benefit and recommendations are made for further research.

1 Introduction

This project is one of five thematic sub-components of the Cooperative Research Centre for Transformations in Mining Economies' (CRC TiME) Operational Solutions Program, which sought to develop a conceptual model of the biophysical impacts of mine closure. The conceptual model to be developed in this landform stability sub-component will be integrated with similar conceptual models from the other thematic sub-components in the Operational Solutions Program into an overall systems model through the program integration process.

There are numerous examples of significant mined landform legacies with inadequate geotechnical, erosional and geochemical stability, and unacceptable closure. These have weighed heavily on the reputation of the industry and have resulted in large financial liabilities for mining companies and/or governments. Understanding past and current mined landform case studies, and why these have either worked or not, provides an important baseline for developing a longer-term research agenda for developing stable mined landforms over the life of the CRC. Importantly, contextual considerations, including the site climate, topography and seismicity, and different mineral commodities, play a critical part.

1.1 Project objectives

The project objectives were:

- to collect and collate information and data on the geotechnical, erosional and geochemical stability, and acceptability for closure, of past and current mined landforms in a range of Australian site settings and for a range of mineral commodities, impacting regional benefit;
- to define the appropriate steps needed for mined landform design and construction;
- to define the information and data required to inform stable mined landform design, focusing on material characterisation;
- to define mined landform construction to ensure stability over time;
- to develop a conceptual model of the often overlooked physical, chemical and biological interactions determining effective mined landform stability post closure in a range of site settings and for a range of mineral commodities in the Australian context;
- to make preliminary recommendations for effective mined landform design, construction and sustainability in the Australian context, and recommendations for further research;
- to present the results of the project to industry; and
- to seek to publish the key findings of the project in refereed journal and/or conference papers.

1.2 Key research questions

The key research questions included:

- What are the key objectives of stable mined landform design?
- What are suitable and acceptable mined landform geometries?
- What are the key steps, information and data needed to inform stable mined landform design, such as material characterisation?
- What is the problem with mined landform stability (from multiple end user, regulator, and other stakeholder perspectives)?

- What defines mined landform instability, what of function, and are there degrees of instability that are acceptable?
- Why do we keep applying some of the same approaches to mined landform design and construction when these continue to fail?
- What disciplines inform mined landform design, such as geology, geotechnical/mining/environmental engineering, hydrology, hydrogeology, geomorphology, soil science, ecology, botany, etc., and how are their differing perspectives combined?
- Why worry about mined landform stability?
- What information already exists (guidelines, practice, reports) from available sources?
- Who else is conducting research in this area; such as the International Network of Acid Prevention (INAP), Landform Design Institute, waste management/landfill?
- What are the challenges/blockers?
- What are the opportunities/enablers?
- What is required to transform this space?
- Should CRC TiME do it or is it being done elsewhere?

1.3 Project deliverables

The deliverables of the project included:

- a set of underpinning published references;
- approach to stable mined landform design;
- effective mined landform design, construction and sustainability in the Australian context, facilitating regional benefits and recommendations for further research;
- presentation of the results of the project to industry and other researchers through the publication of the key findings of the project in refereed journal and/or conference papers.

The project lends itself to integration with similar thematic sub-components in CRC TiME's Operational Solutions Program into an overall systems model through the program integration process.

1.4 Project activities, strategy and methodology

The Research Plan comprised the following activities:

- searching published information and data on mined landforms, covering a range of Australian site settings and mineral commodities, in refereed journal and conference papers and industry and government publications;
- searching unpublished information and data on mined landforms, covering a range of site settings and mineral commodities, from members of the project research and industry end user teams;
- presenting case studies of effective mined landform stability post-closure in a range of site settings and for a range of mineral commodities in the Australian context;
- making recommendations for further research on effective mined landform design, construction and sustainability in the Australian context, and;
- presenting the results of the project to industry and other researchers through the publication of the key findings of the project in refereed journal and/or conference papers.

The project focused on the mine site case studies listed in Table 1, which cover a range of Australian mine site settings and mineral commodities, and associated regional benefits. The prime example of value-adding post-closure is the Kidston Genex Renewable Energy Hub, with Sovereign Hill a long-standing example of the conversion of a mine (the lure of gold in this case) to a tourist attraction. The other case studies involve more conventional rehabilitation of the mine sites, or elements of them, to achieve improved environmental and regional outcomes, while adding post-mining value.

Table 1: Mine site case studies considered in the project

SITE	DESCRIPTION
Kidston Genex, North Queensland	Rehabilitated by 2001, Genex constructed a Solar Farm on the tailings storage facility in 2017, and is constructing a Pumped Storage Hydro utilising the two pits
New Century, North Queensland	Reprocessing of tailings for zinc and final in-pit disposal
New Acland Coal Mine, South-East Queensland	Rehabilitating surface and in-pit tailings storage facilities, and backfilling of pits with spoil, for return to grazing
McArthur River Zinc Mine, Northern Territory	Rehabilitating waste rock dump to restore license to operate
Bengalla Coal Mine, Hunter Valley, New South Wales	Rehabilitating spoil piles for a visual bund and grazing
Loy Yang Mine, Latrobe Valley, Victoria	Progressive rehabilitation of Loy Yang overburden dump
Sovereign Hill, Victoria	Repurposing of abandoned old gold workings for tourism
Henty Gold Mine, West Coast of Tasmania	Combined peat and water cover over sulfidic tailings
Kanmantoo Copper Mine, South Australia	Integrated waste landform
Collie Coal Mine, South-West Western Australia	Lake Kepwari pit lake relinquishment
Beenup Mineral Sands Mine, South-West Western Australia	Wetland rehabilitation and relinquishment
Pardoo Iron Ore Mine, Pilbara, Western Australia	Waste rock dump rehabilitation

1.5 Project resources

The resources that contributed to the project and the name of each contributing party, were as follows:

Research Team:

- The University of Queensland:
  - Professor David Williams – Project Leader – Geotechnical aspects of mined landform stability
- Federation University:
  - Professor Thomas Baumgartl – Geoscience aspects of mined landform stability

Industry End User Team:

- Antonia Scrase (Energy Australia Yallourn) – End User Sponsor
- Dr Rob Loch (Landloch)
- Craig Lockhart (BHP)
- Jodie Belton (Rio Tinto)
- Ben Walley (Newmont)
- Jonathon Crosbie (MMG)
- Venicia de San Miguel (Roy Hill)
- Chris Waygood (Golder)
- Julian Krugger (Emapper)
- Katina Strelein (Lyonesse Consulting)
- Ainsley Ferrier (Deswik)
- Colm Molloy (Aurecon)
- Andrew Haslam (Downer)
- Andrew Grabski (DNRME, QLD)
- Katrina Nagle (DEM, SA)
- Dr Mike Saynor (ERISS Ecosystem Restoration and Landform program)

The bulk of the project was carried out by Professor Williams, with review comments provided by contributors from among the project research and industry end user teams and by CRC TiME personnel.

2 Key issues driving mine closure transition

The key issues driving mined landform stability transitioning for regional benefits are to plan, design, construct, operate and close a mine to achieve a safe, stable, and non-polluting mined landform in perpetuity, with the potential to add regional benefit. This can be challenging because of the site settings, particularly the variable climate in Australia, and because of cost pressures and perceptions.

2.1 Importance of site settings

While Australia's short recorded history of earthquakes shows low seismicity, post-closure mined landforms are required to be safe, stable, non-polluting, and to meet an agreed post-mining land use or ecological function in perpetuity. "In perpetuity" is difficult to quantify, and is typically taken to be 10,000 years (adopted from the long-standing return interval for nuclear power stations), meaning that post-mining landforms must be designed to withstand 1 in 10,000-year flooding and seismic loading. For seismic loading, this requires a projection into the future of two orders of magnitude from the typically 100 years of available seismic data. The 1 in 10,000-year earthquake for Australia is probably of the order of a magnitude 7.5 event, comparable to about the 1 in 100-year earthquake for San Francisco, which history has shown kills people and leads to widespread damage to infrastructure and the environment. This scenario is hardly safe and stable.

Australia is *"a land of droughts and flooding rains"* (from Dorothea Mackellar's poem "My Country"), which recent history in eastern Australia has again demonstrated. While mean annual rainfall is often quoted, this does not capture the wide range in annual rainfall totals for much of Australia, let alone severe rainfall events lasting for days or weeks. For much of Australia, the range of annual rainfall can be from about half the average to twice the average, and it is the high rainfall years and severe rainfall events, particularly when they are back-to-back, that lead to high rates of potentially contaminated seepage from mine waste landforms, can overtop pits containing potentially contaminated water, and lead to high erosion rates. Climate change is exacerbating the frequency and severity of extreme events.

Further, annual rainfall is reported on a calendar year basis. While this may be appropriate for the Mediterranean climate of much of the southern half of Australia because the wet season occurs in the middle of the year, it is not so appropriate for the northern half of Australia, where much of the mining activity now takes place. In the northern half of Australia, the wet season straddles the end of one year and the beginning of the next. Splitting the wet season over two years may underestimate its magnitude.

2.2 Impact of net present value accounting

Net present value (NPV) accounting with a high discount factor, typically in the range from sixto 10%, dominates the mining industry. It is intended to discount future expenditure to the current cost base, and has the effect of delaying expenditure, in the belief that delay will result in a cheaper cost. The impact of NPV is compounding, hence its impact is limited for a mine with a short life of only a few years, but large for a long-term mine (which could be as long as 100 years).

According to the GARD Guide (2009), closure options decrease and costs increase with time (Figure 1), which is somewhat counter to NPV accounting with a high discount factor. Whole-of-life accounting is encouraged, if closure is to not only be effective, but also cost-effective.

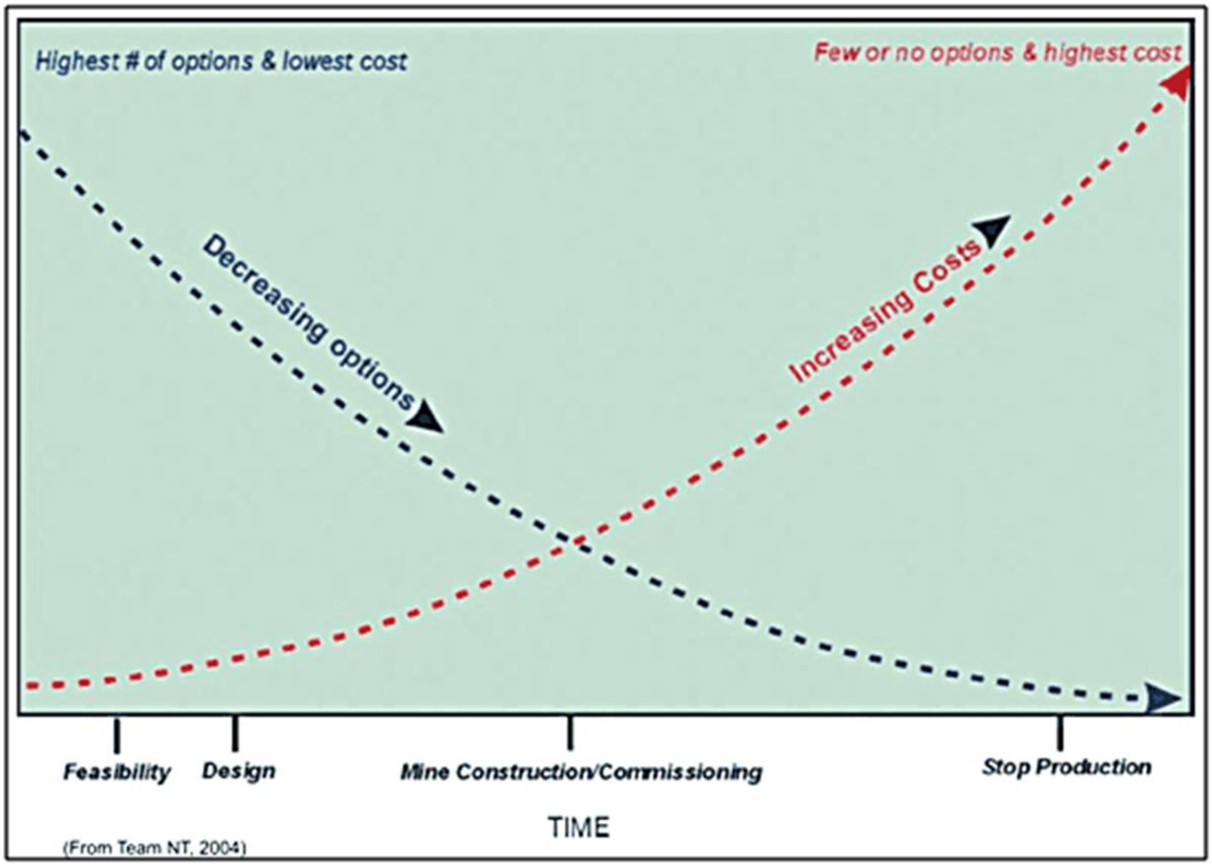


Figure 1: Closure options decrease and costs increase with time

2.3 Open pit versus underground versus block cave mining

The depth of overburden and ore grade dictate the economics of open pit versus underground mining. With open pit mining representing over 70% of mining in Australia, open pit mining is the main focus of the case studies considered in this project. Block caves are increasingly replacing or extending deep open pits, and generally result in subsidence of the surface, that can be of comparable size to large open pits.

Obviously, open pit mining creates the largest disturbed footprint and involves the most movement of material; including waste rock, and lower grade ore that is economic to mine on a large-scale by open pit methods, creating higher volumes of tailings to be stored. Large block caves largely avoid the transport of waste rock, but are likely to generate similar volumes of tailings to a comparable open pit operation. Underground mines generate small volumes of waste rock that may remain underground, and reduced volumes of tailings because they are small-scale and target high-grade ores.

2.4 Surface waste rock management

Waste rock produced on open pit mining is expensive to haul and about five 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. In order to minimise waste rock haulage costs, surface waste rock dumps 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 2 (Williams, 2014).

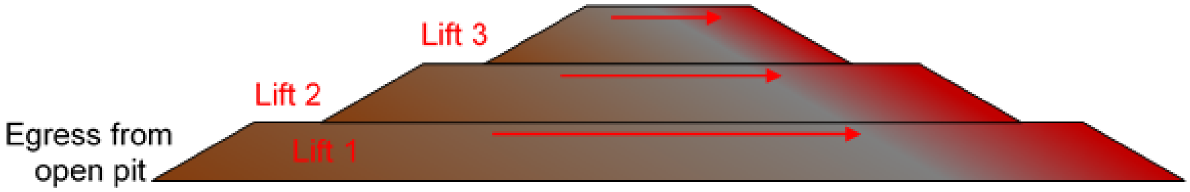


Figure 2: Schematic of typical waste rock dumping

As a result, unless steps are taken to avoid it, the weathered (or oxidised) surficial overburden is dumped on the base of the waste rock dump and close to the pit, while any sulfidic waste rock (depicted in red in Figure 2) from deeper in the pit below the groundwater table, is dumped further away from the pit and higher in the dump.

In addition, the conventional end-dumping of waste rock in a surface dump produces “oxidation reactors” as shown in Figure 3 (GARD Guide, 2009), involving a base rubble zone formed by the raveling 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 present 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, challenging rehabilitation.

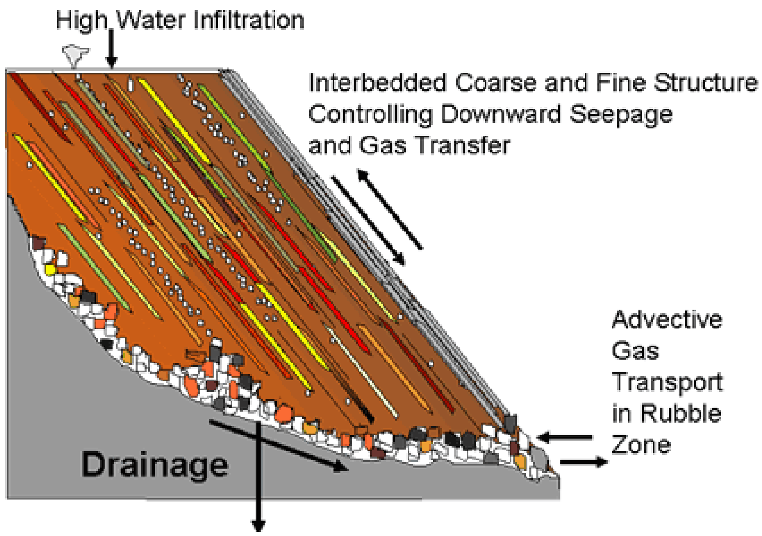


Figure 3: Conventional end-dumping of waste rock in a surface dump

Provided that it will not sterilise future resources, consideration may be given to backfilling the open pit with waste rock, particularly with potentially acid forming (PAF) waste rock that would pose a risk of acid and metalliferous drainage (AMD) if placed in surface waste rock dumps.

Both waste rock dumps 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 tailings storage facility will increase, forcing consideration of both the tailings and the waste rock storages being located close to the pit.

2.5 Tailings management

Conventional tailings storage involves the delivery of thickened tailings using inexpensive and robust centrifugal pumps to a surface facility that is raised progressively to delay costs. The tailings form a beach on which they settle, consolidate, and desiccate if exposed to sun and wind. The tailings embankment (or dam) is raised by the upstream method partially on beached tailings, downstream or by the centreline method (Figure 4), and the operating dam is not necessarily designed to be safe, stable and non-polluting in perpetuity post-closure. The tailings entrain considerable water, adding to the volume required to store them, and with the potential to produce contaminated spillway flow and to drain down and potentially produce contaminated seepage through the dam or to the groundwater.

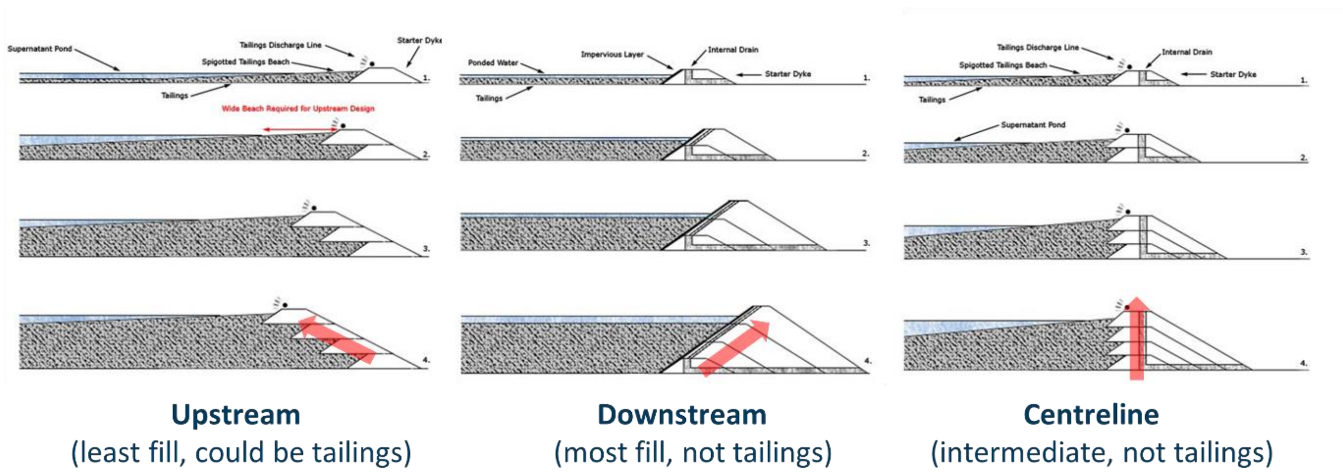


Figure 4: Surface tailings dam construction methods (Source: www.tailings.info)

Upstream construction is well-suited to dry climatic regions of Australia, and requires that the tailings be made a suitable foundation to support the next raise. This requires that the rate of rise of the tailings is limited to less than about 2m/year, that the tailings are deposited in thin lifts (of the order of 0.3m) and given sufficient time to consolidate and desiccate by exposure to sun and wind, and that water not be allowed to collect against the dam. It may be possible to use dried tailings to construct the majority of and upstream raise, with rip rap applied to the crest and downstream slope for erosion control. Downstream construction is more like a conventional water dam, although it requires substantially more fill than upstream construction (Figure 5).

Tailings can also be deposited in a completed pit, provided that this does not “sterilise” future resources, or lead to the pit becoming a “source” of contaminated water. The deep geometry of a pit (steep sides and small footprint) compared with the necessarily flat geometry of a surface tailings storage facility (low dam and large footprint) results in a very high rate of rise of tailings in-pit (up to 10 times the rate of rise in a surface facility). Also, in-pit tailings deposition is typically underwater because of the difficulty of removing water from the pit as the tailings and hence water levels rise. Even if pit water can be removed, shadowing and reduced wind due to the pit walls reduce desiccation of the exposed tailings surface. As a result of the high rate of rise and lack of or limited desiccation, in-pit tailings may not fully consolidate and are unlikely to significantly desiccate (if at all), filling the pit rapidly, largely with entrained water. The result is an in-pit tailings deposit of very low density and very low strength, making them difficult to rehabilitate other than by using a water cover or end-dumping large quantities of waste rock that will displace much of the water and tailings before forming a safe and stable cover.

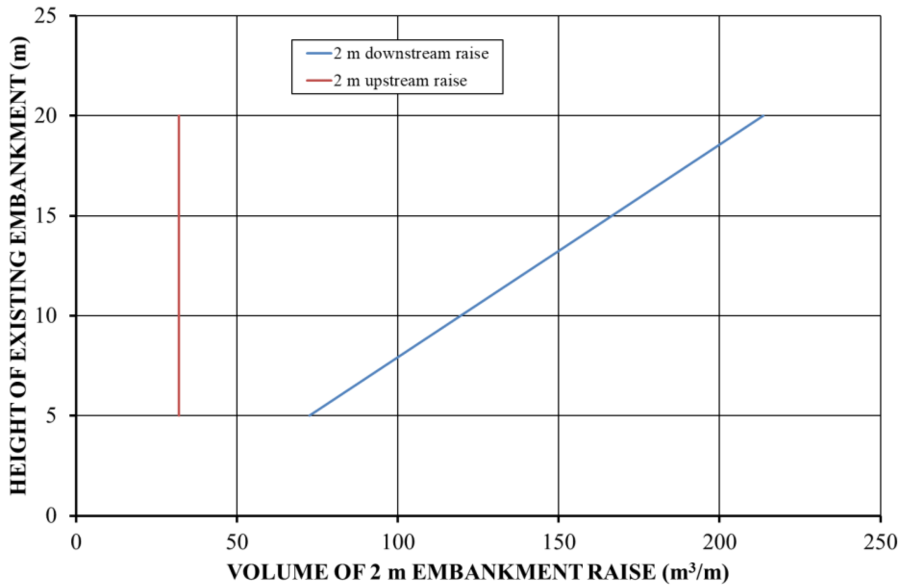


Figure 5: Relative fill volume requirement for upstream and downstream surface tailings embankment construction

Tailings destined for in-pit disposal could be thickened to a paste and fed by gravity into the pit, avoiding the need for expensive positive displacement pumps. This also enables valuable process water and chemicals to be recovered for re-use, rather than being lost to entrainment, evaporation and seepage. Tailings may also be beneficially used to backfill underground mines, either to avoid the surface storage of tailings or as cemented backfill to enable ongoing underground mining. This requires the tailings to be thickened to a non-draining paste, which can be delivered underground by gravity provided that the intended destination underground is located at an angle in excess of about 45° to the point of disposal (usually a borehole).

There is a strong argument for “integrated waste landforms”, in which the strength of waste rock is engaged to construct stable and robust landforms, removing “credible failure modes” that might cause extreme consequences, with the tailings stored safety behind them. In this case, the tailings could be delivered as a conventional thickened slurry, or a paste, or a filter cake, depending on what best suits the operation and their post-closure goals. There are also strong arguments for the greater dewatering of tailings to minimise their storage requirements, and to increase their strength to support rehabilitation works and add value post-closure. Being flat, a tailings beach is well-suited to future land use if it can support the loading involved. Further, there are strong arguments for reducing the volume of tailings slurry produced by employing coarse and/or dry processing. There are also opportunities to reprocess tailings to recover remnant minerals, and to handle the residual tailings more cost-effectively.

2.6 Closure risks and challenges

Closure risks and challenges for open pits include pit slope instability, both geotechnical and erosional, and poor pit water quality. In a net evaporative climate, without additional surface inflows, pit water quality is likely to become increasingly saline and possibly more acidic if the pit slopes expose sulfides, due to evaporative concentration, but is also likely to remain a groundwater “sink”. In a wet climate, the pit may become a groundwater “source”, and possibly risk overtopping, possibly releasing acidic water if the pit slopes expose sulfides.

Closure risks and challenges for block caves include ongoing toppling and erosional instability of the steep edge of the surface expression of the block cave, aided by rainfall ingress into cracks; ongoing subsidence; and poor water quality. Similar to open pits, water levels and quality of block caves is dependent on the climate and inflows.

Closure risks and challenges for surface waste rock dumps include slope instability; possibly geotechnical or, more likely, erosional, particularly in a dry climate if 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 swell because the secondary minerals formed occupy more volume, while the spontaneous combustion of sulfidic coal reject or spoil will lead to collapse because of the combustion of carbonaceous material present. Seepage water quality from waste rock dumps can be saline and/or acidic, likely after a geochemical and/or hydrological (taking time for the dump to wet-up sufficiently and requiring significant rainfall events for seepage to emerge) lag. Seepage will likely emerge at low points around the toe of the waste rock dump, or report to the foundation beneath the dump, and potentially to groundwater. Runoff from waste rock dumps could carry erosion sediment and/or any contaminants.

Closure risks and challenges for surface tailings storage facilities include dam geotechnical instability, although in a dry climate after the cessation of tailings deposition the tailings would be expected to drain down, improving geotechnical stability. However, in a wet region of Australia, such as the northern wet tropics or the west coast of Tasmania, or during extreme rainfall events, the tailings may be resaturated. The dam and the tailings themselves or any cover over the tailings could be subject to erosional instability in extreme rainfall events, particularly bare tailings or topsoil, although this is unlikely to affect geotechnical stability. In addition, differential settlement of the loosely-deposited and draining tailings can affect their final profile and drainage. The spontaneous combustion of high sulfide tailings can lead to swell because the secondary minerals formed occupy more volume, while the spontaneous combustion of sulfidic coal tailings will lead to collapse because of the combustion of carbonaceous material present. Seepage and runoff water quality from surface tailings storage facilities can be saline, and/or acidic, and/or alkaline, likely after a geochemical lag depending on the exposure of the tailings to oxygen. Seepage will likely emerge at low points around the toe of the tailings dam, or report to the foundation beneath the facility, and potentially to groundwater. Runoff from surface tailings storage facilities could carry erosion sediment and/or any contaminants. In-pit tailings could cause the pit to become a “source” of sediment-laden and/or contaminated water, or to overtop carrying sediment and/or contaminants.

2.7 What constitutes a stable mined landform?

The well-accepted overarching requirement for mine sites post-closure is safe, stable and non-polluting landforms in perpetuity that are able to sustain an agreed post-closure land use or ecological function (DMIRS, 2020 and DES, 2021). However, very few mines have been successfully rehabilitated and relinquished.

The rehabilitation of open pits is often limited to bunding and fencing around the crest (Figure 6). In some cases, open pits are backfilled or converted to lakes (Figure 7). No block caves have been successfully rehabilitated, leaving an unstable subsidence zone (Figure 8).

Some waste rock dumps have been successfully rehabilitated (although very few have been relinquished), with potentially contaminating waste rock (such as PAF) typically 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 9).

Some tailings storage facilities, both surface and in-pit and in a range of climates, have been successfully rehabilitated (Figure 10; very few have been relinquished), with reprocessing and in-pit disposal increasingly being considered to remove the surface tailings facility and avoid the difficulties and cost of its rehabilitation.

Figure 6: Bunding and fencing around crest of a closed open pit

(a)

(b)

Figure 7: Open pit examples: (a) backfilling, and (b) flooding

Figure 8: Unrehabilitated block cave

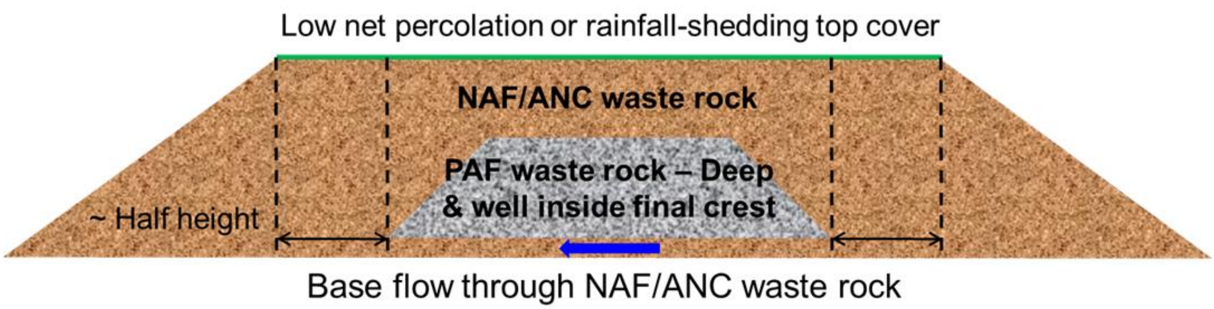
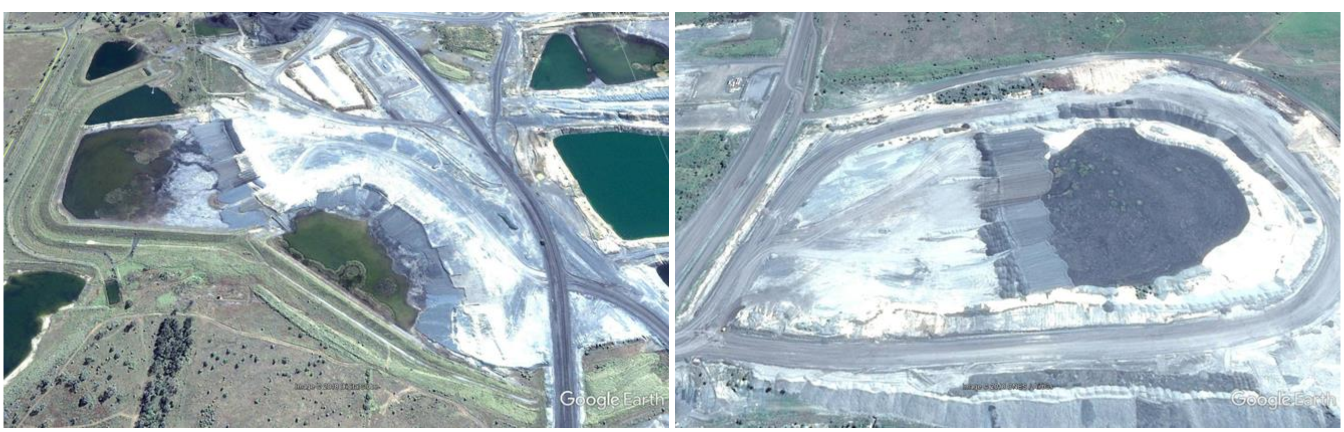


Figure 9: Leading practice encapsulation and covering of potentially contaminating waste rock



(a) (b)

(c)

Figure 10: Successful rehabilitation of tailings facilities: (a) surface coal tailings, (b) in-pit coal tailings, and (c) sulfidic tailings in a cool, wet climate

2.8 Value-added mine site rehabilitation

Both mine operators and regulators focus on the cost of mine site rehabilitation, essentially assuming that the rehabilitated mine site will be unproductive post-closure (Williams, 2019). In fact, all activities on a mine site involve a cost, which must be allowed for in the assessment of the value of the commodity produced. In meeting rehabilitation requirements and expectations, the cost of mine site rehabilitation and the loss of revenue at closure results in a focus on attempting to recover rehabilitation costs. This leads to the removal of infrastructure with some scrap value, such as the copper and steel in electricity transmission lines, and building materials. There is a need for a change in the narrative surrounding mine site rehabilitation to re-focus on post-mining "value" rather than "cost", as is illustrated in Table 2.

Table 2: Conventional "cost" versus alternative "value-added" approaches to mine site rehabilitation

CONVENTIONAL COST-BASED REHABILITATION	ALTERNATIVE VALUE-ADDED REHABILITATION
Production rules	Post-closure "value" is identified upfront
Rehabilitation is seen by operator and regulator as a "cost" Operator discounts cost over time, discouraging rehabilitation Infrastructure such as power lines are stripped and sold for small gain	Examples include: • Renewable energy – solar, wind and pumped storage, delivered to grid via mine transmission lines, if possible • Agriculture and/or fishery using water dams • Tourism and heritage (the older, the better)
Rehabilitation is limited to "smoothing" and "greening"	"Value" sets rehabilitation budget
Post-closure land use and function are limited	Potential wins for operator, future land user and Government

3 Mine site case studies

The mine site case studies considered in the project, as listed in Table 1, are presented in the following sections, which detail the site setting, the nature and storage of the wastes generated, the rehabilitation approach and success, and any regional benefits post-closure. Most of the mine site case studies are in relatively flat terrain, and of low seismicity, and these aspects are not discussed in detail, while their climatic settings vary and these are discussed. Australia's generally relatively flat terrain limits the "free storage" available in valleys, particularly for tailings storage, and also limits the height to which both waste rock dumps and tailings dams can sensibly be taken.

The amount of information available on each of the mine site case studies varied, which is reflected in the extent of their respective sections. The most information available was for the Kidston Genex site – this site is overwhelmingly the best example of post-closure regional benefit. For the other mine site case studies, the available information was much more limited and only information pertinent to the particular focus topic of the site is provided.

3.1 Kidston Genex, North Queensland

This section provides a very comprehensive overview of the state of the two open pits, the rehabilitation of the Kidston Gold Mines surface waste rock dump and tailings storage facility, the construction by Genex of the Solar Farm on the tailings storage facility, the current construction by Genex of the Pumped Storage Hydro Project involving the two pits, and the sustainability of the Genex Projects at the Kidston site.

Figure 11 shows a Google Earth image of the Kidston Gold Mines site, located 270km north-west of Townsville in North Queensland. Kidston mined Wises Hill Pit extending to a depth of about 240m (52ha footprint), followed by Eldridge Pit extending to a depth of about 270m (54ha footprint). The waste rock and tailings generated from Wises Hill Pit were placed in a surface waste rock dump surrounding the former Wises Hill and a large surface tailings storage facility, respectively. The surface waste rock dump has a typical height of about 36m constructed in a single lift, with a total area of 337ha. The surface waste rock dump sits on Wises Hill, which has a low permeability, limiting rainfall and seepage infiltration. The tailings storage facility has a maximum embankment height of about 32m, an average tailings depth of about 15m, and an area of 310ha in a total catchment of 414ha.

All of the waste rock and tailings generated from Eldridge Pit were backfilled into the completed Wises Hill Pit, the waste rock end-dumped from the north-west crest of the pit (upper right in Figure 11), and the tailings thickened and gravity-fed down the opposite southern crest of the pit.

Figure 12 shows an aerial view of the Kidston Genex site, with the Solar Farm on the surface tailings storage facility to the top left, and the two partially flooded open pits that will be converted into a Pumped Storage Hydro Project; the backfilled Wises Hill Pit in the centre surrounded by the waste rock dump, and Eldridge Pit to the lower left of Figure 12.

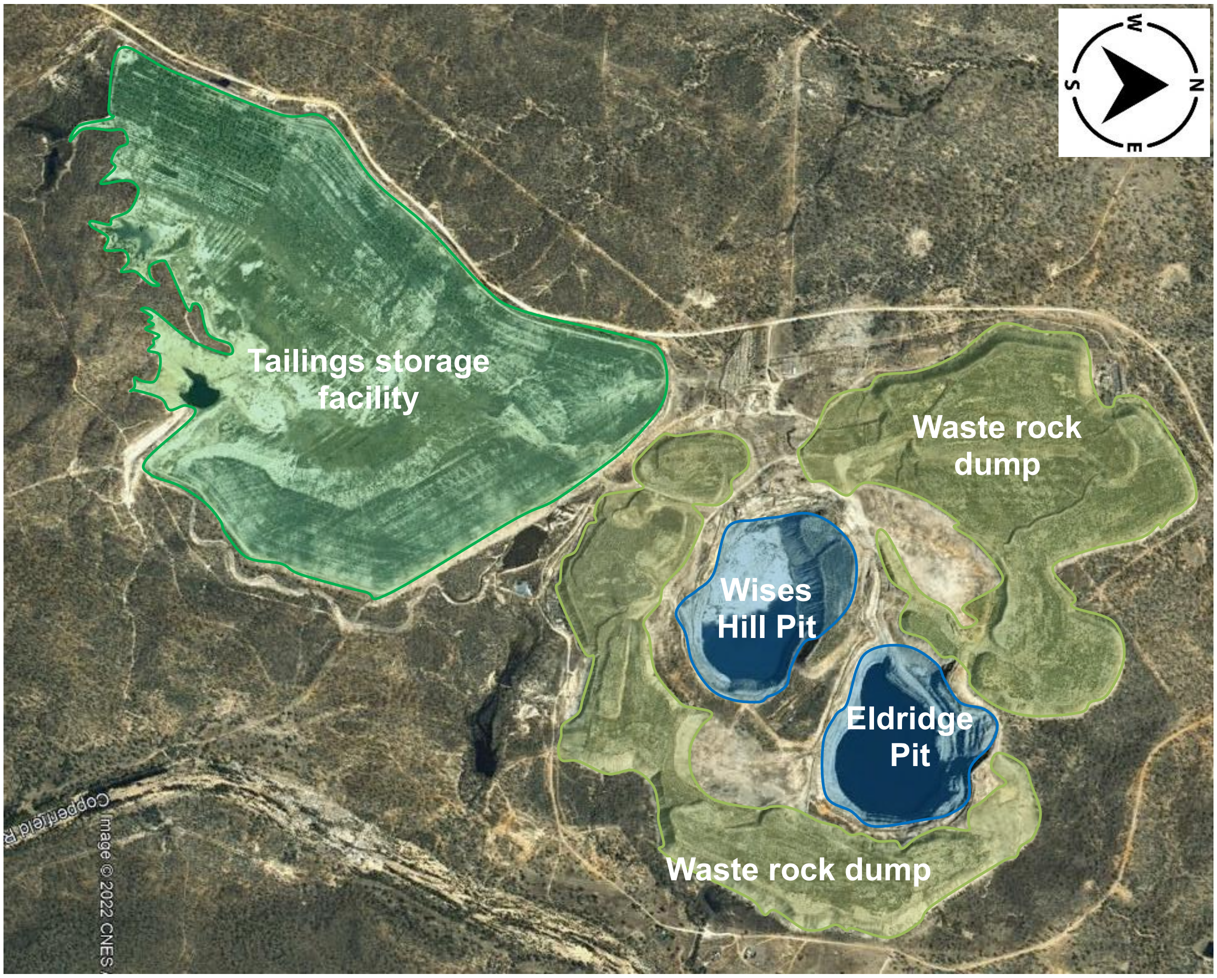


Figure 11: Google Earth image of Kidston Mine Site (December 2016)

Figure 12: Aerial view of Kidston Genex site

3.1.1 Climatic setting

The Kidston Genex site experiences a sub-tropical hot and humid wet season (December to March) and long cooler dry season (April to November; www.bom.gov.au). Figure 13 shows long-term rainfall data for the site since 1902, with the Kidston mining and rehabilitation timeframes overlain (mining from 1984 to 2001 and rehabilitation from 1995 to 2001). Figure 13 shows a rising trend in annual rainfall over time, from a low of about 620mm in 1940 to over 800mm in 2020. The historical mean annual rainfall is 656mm, and the range is from 126mm in 1926 to 1,588mm in 1974 (20 to 240% of the average). Since the rehabilitation and closure of Kidston Mine, the mean annual rainfall has been 795mm, with a range from 539mm in 2002 to 1,572mm in 2009 (68 to 198% of the average). Figure 14 shows the variation in monthly rainfall, including the average, lowest and highest monthly rainfalls recorded over the last 120 years. The average number of days of rain/year is 68 days, or only 19% of the year. The site climate is strongly net evaporative on average.

The 2010/11 wet season (1,572mm of rain fell in 2010) swamped the seepage collection ponds and pump-back to the pits, and required Barrick, the then owner of the Kidston site, to undertake major work to increase the storage capacity of the seepage collection ponds and the scale of the pump-back system.

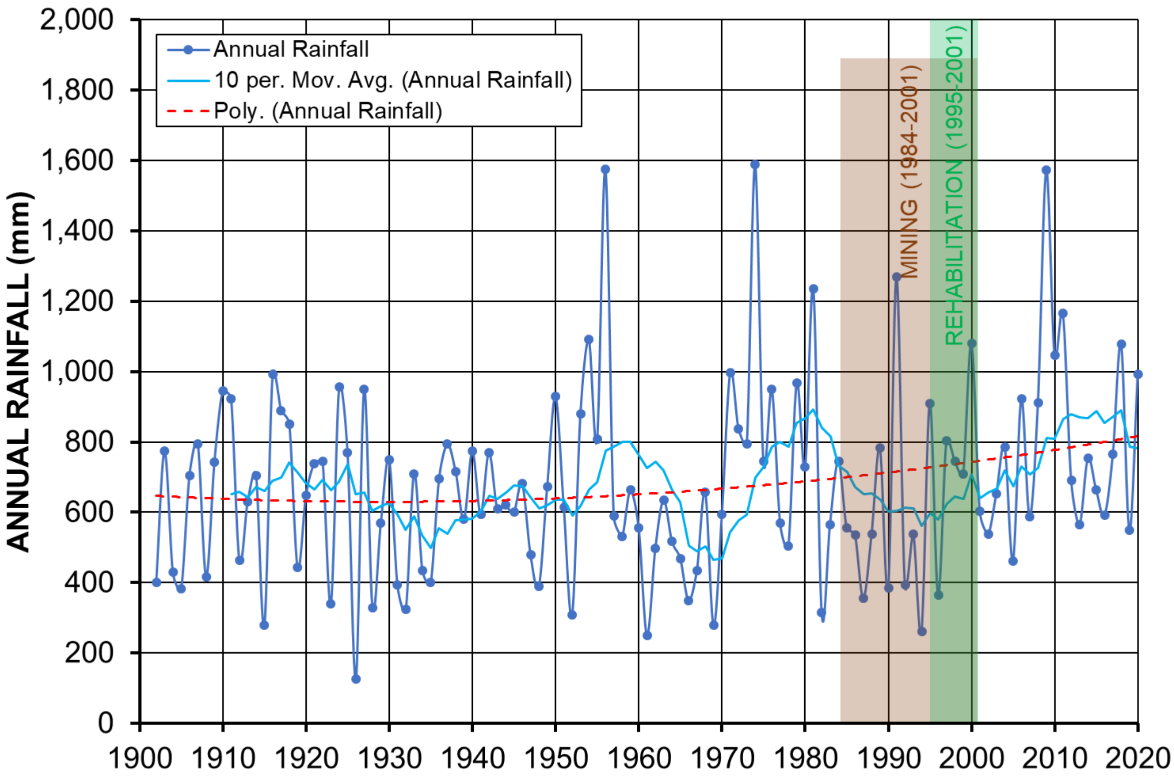


Figure 13: Long-term rainfall data representative of Kidston

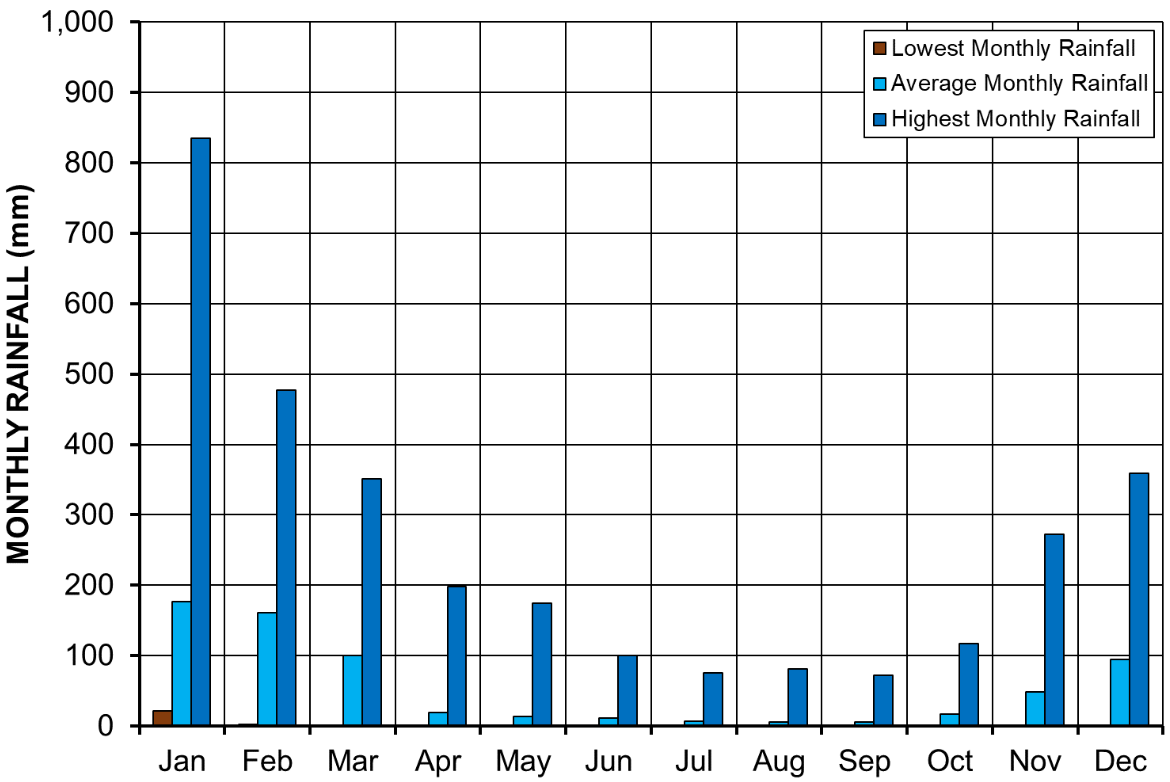


Figure 14: Monthly rainfall data representative of Kidston

3.1.2 State of open pits

Hydrogeological studies have demonstrated that the pits will remain groundwater sinks and the rock surrounding the pits is tight, as evidenced by the limited drawdown of the groundwater surrounding the pits during mining. The seepage from the surface waste rock dump and tailings storage facility is collected in ponds and pumped to Eldridge Pit, and has little impact on its volume or water quality.

Wises Pit water has a relatively high electrical conductivity (typically 6.6 dS/m), circum-neutral pH (typically about 8.1), is elevated in sulfate (typically 3,700 mg/L), and somewhat elevated in arsenic, cadmium, and nickel. Eldridge Pit water has a moderate electrical conductivity (typically 3.1 dS/m), circum-neutral pH (typically about 7.4), is moderately elevated in sulfate (typically 1,600 mg/L), and somewhat elevated in arsenic, cadmium, copper, manganese and nickel.

3.1.3 Rehabilitation of surface waste rock dump

The Kidston waste rock comprised less than 20% mineralised (PAF) material, which had a typical sulfur content of 0.9%, and typically 1.8 times the acid neutralisation capacity, making it potentially susceptible to acid generation in extreme wet seasons. The remainder of the Kidston waste rock comprised mostly fresh barren (NAF) rock, plus surficial weathered rock or oxide waste. There was minimal topsoil, with the upper oxide layer serving as the natural growth medium. The oxide waste was NAF, but highly erodible, particularly on steep slopes.

The strategy adopted by Kidston for the construction of their surface waste rock dump was to selectively place the mineralised material within a 50 to 60m wide side encapsulation of fresh barren rock, and to construct a cover comprising oxide waste over the top of the dump. The aims were to prevent the exposure of the mineralised material to rainfall infiltration incident on the free-draining fresh barren rock angle of repose slopes, and for the top cover to minimise the net percolation of incident rainfall into any underlying mineralised material.

The rehabilitation strategy developed for the surface waste rock dump took into account the intense wet season and long dry season, the need to minimise the net percolation of rainfall into the encapsulated mineralised waste rock, and the erodibility of the oxide waste. A “new” robust, non-shedding, erosion-resistant store and release cover system was developed for the top of the waste rock dump, as later endorsed for the climatic setting of the site by the GARD Guide (2009), as shown in Figure 15.

The principle behind the store and release cover system was to “store” the wet season rainfall and “release” the stored water through evapotranspiration during the long dry season, with the moisture state of the cover cycling seasonally between wet and dry, and no net wetting-up or drying-out of the cover over time. The success of a store and release cover is dependent on a low permeability layer at the base to “hold-up” rainfall infiltration in the upper growth medium, and the revegetation to release it, with the sustainability of the revegetation in turn dependent on it. A natural analogue to the store and release cover system is a paleochannel, with water held-up in the coarse-grained channel by a layer of low permeability sediment beneath it, and sustaining vegetation along the channel.

Bews et al. (1997) described the design and trialing of the store and release cover system for the top of the waste rock dump, shown schematically in Figure 16. The adopted design was a 500mm compacted layer of selected fine-grained, highly-weathered oxide waste to "hold-up" rainfall infiltration, overlain by a nominal 1.5m thick, loose-dumped, mounded "rocky soil mulch" layer of highly-weathered oxide waste to serve as an evapotranspirative growth medium for trees, shrubs and grasses. The initial trial covers involved truck paddock-dumped rocky soil mulch, which were later smoothed by low-bearing pressure dozers to "smear" potential seepage flow paths to the base of the rocky soil mulch layer, while still not shedding erosive rainfall.

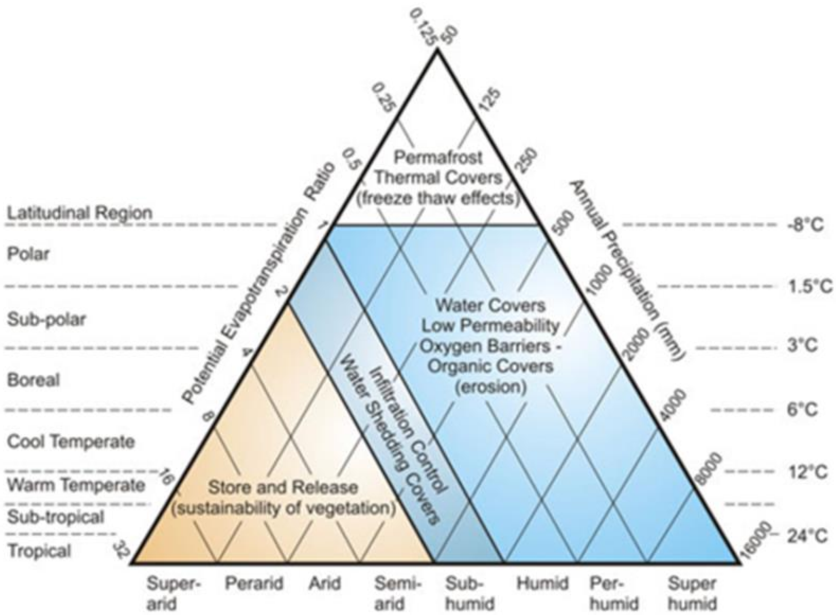


Figure 15: Selection of cover system based on climatic setting

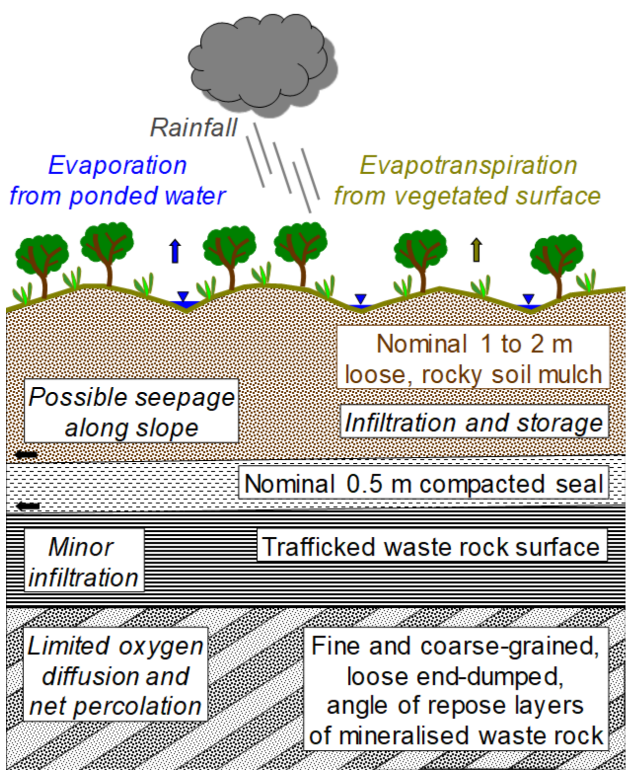


Figure 16: Schematic of store and release cover system developed for Kidston waste rock dump top

During the first 6 years (Williams et al. 2003), the 23ha instrumented store and release cover trial recorded an average net percolation of rainfall of 0.25%, with a maximum of 1.1%. The annual rainfall totals during this period were 524mm, 623mm, 475mm, 522mm, 713mm and 523mm, typically well below the then long-term mean annual rainfall of 656mm, which also impacted revegetation. The intermittent ponding of rainfall between the store and release cover mounds was observed following rainfall events during each wet season. The gravimetric moisture content of the rocky soil mulch layer cycled between a minimum of about 4% (about 20% saturated) at the end of each dry season and about 13% (about 70% saturated) during the wet season.

The estimated (unsaturated) hydraulic conductivity of the surficial rocky soil mulch beneath ponded rainfall was about 15 mm/day (1.7×10^{-7} m/s), resulting in a wetting front that penetrated about 250mm into the rocky soil mulch layer before the pond disappeared. Evaporation from the ponded rainfall averaged about 11 mm/day.

Water uptake by 2- to 3-year-old eucalypts ranged from 2 to 20 L/day/tree during the late dry season (October) to 10 to 30 L/day/tree during the wet season, making eucalypts the key to sustainable transpiration. Water uptake by 2 to 3-year old acacias was 3 to 4 L/day/tree during October. Water uptake by grass cover was 2 to 4 mm/day. Overall, the water uptake by revegetation varied between about 2 mm/day in the dry season to 4 to 6 mm/day during the wet season, compared with an annual average daily rainfall of about 2mm, demonstrating that the cover was generally net evaportransporative.

Prior to the 23ha store and release cover being constructed on part of the waste rock dump, the seepage rate at the toe averaged 4 to 5 L/s. The cover reduced this by about 30%. Following the covering of the entire waste rock dump, the seepage rate reduced to <1 L/s or <1.4% of annual rainfall incident on the top of the dump. This seepage included ongoing but diminishing drain down of the waste rock dump wet-up by rainfall during its construction and net percolation through the store and release cover estimated to be <1% of annual rainfall.

Williams et al. (2006) confirmed the findings reported in Williams et al. (2003), and reported reducing seepage flows and improving quality. V-notch weirs were installed on the main toe seeps from the waste rock dump in October 2002, and measured a reduction in flows to about 0.6 L/s by August 2005. Figure 17 shows the onset of mild AMD, particularly during the 1990/1991 extreme wet season (1,269mm of rainfall was recorded in 1991), which resulted in the pH of the seepage dropping suddenly from about 7.5 to about 4.5, and the sudden increase in dissolved copper and zinc. Figure 17 also shows reducing copper and zinc concentrations in the seepage following the completion of the covers on the waste rock dump. While water quality in the seepage collection ponds at low points around the toe of the surface WRD remains acidic and has elevated dissolved copper and zinc, water quality downstream of the site is generally in compliance with regulatory limits.

The pump-back of seepage from the surface waste rock dump toe seepage collection ponds to the pits provides an indicator of seepage rates from the facility, and increases with rainfall, although it will be somewhat lagged in time. Mean annual seepage from the waste rock dump is estimated from pumping records to be up to 2.2% of rainfall incident on the dump (at 1.8 L/s), allowing for evaporation from the seepage collection ponds of 0.3% of rainfall, and negating any seepage into the foundation. Of the 2.2% seepage, the uncovered side slopes account for an estimated 1.4% (assuming 50% rainfall infiltration), implying an estimated 0.8% net percolation through the store and release covers, which is as good as any cover would be expected to achieve.

The development of mean total revegetation cover on the top of the waste rock dump during the 20-year period since the completion of rehabilitation in 2001 is a high 82% (CSIRO, 2021), as shown in Figure 18. Unremarkably, the percentage of green or living revegetation cover has fluctuated seasonally. Importantly, however, "bare ground" has steadily declined to average 13% over the past 5 years. Apart from good density, the revegetation also shows considerable diversity, with tree, shrub and grass cover, as shown in Figure 19.

Since the oxide waste was found to be highly erodible on slopes, the fresh barren waste rock side slopes of the waste rock dump were left at their angle of repose and partially over-dumped with oxide waste to promote moisture retention and revegetation (Figure 20). Recent dry season photographs of the side slopes of the waste rock dump are shown in Figure 21.

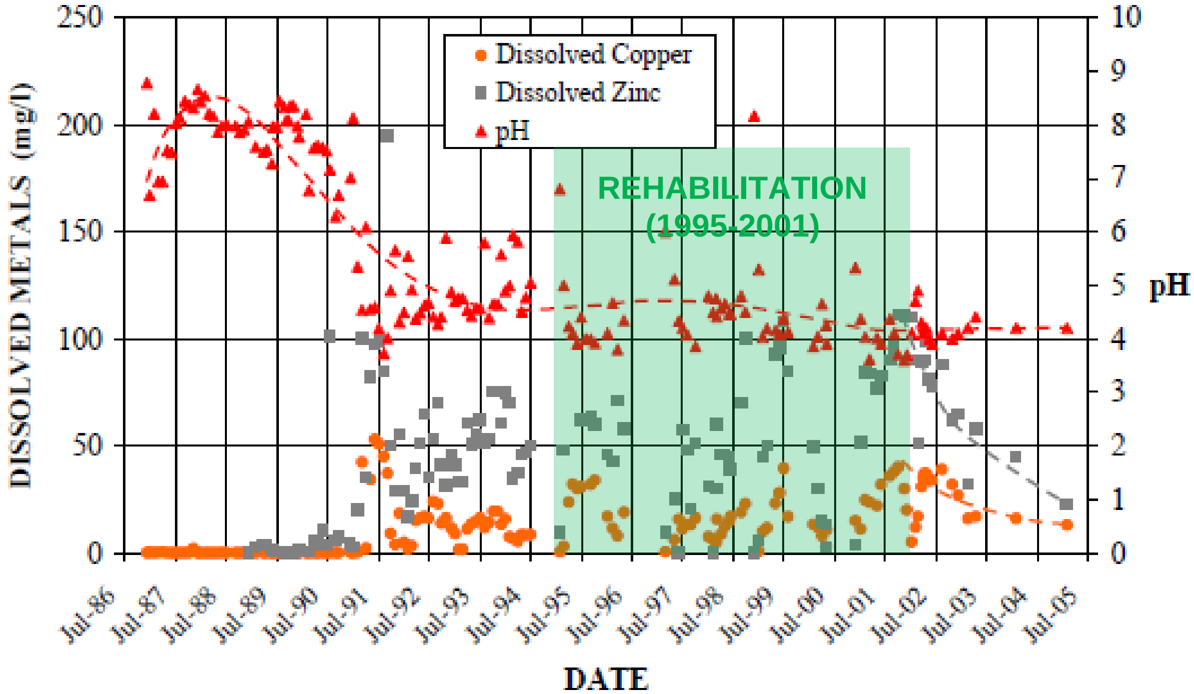


Figure 17: Improving seepage quality after completion of store and release covers

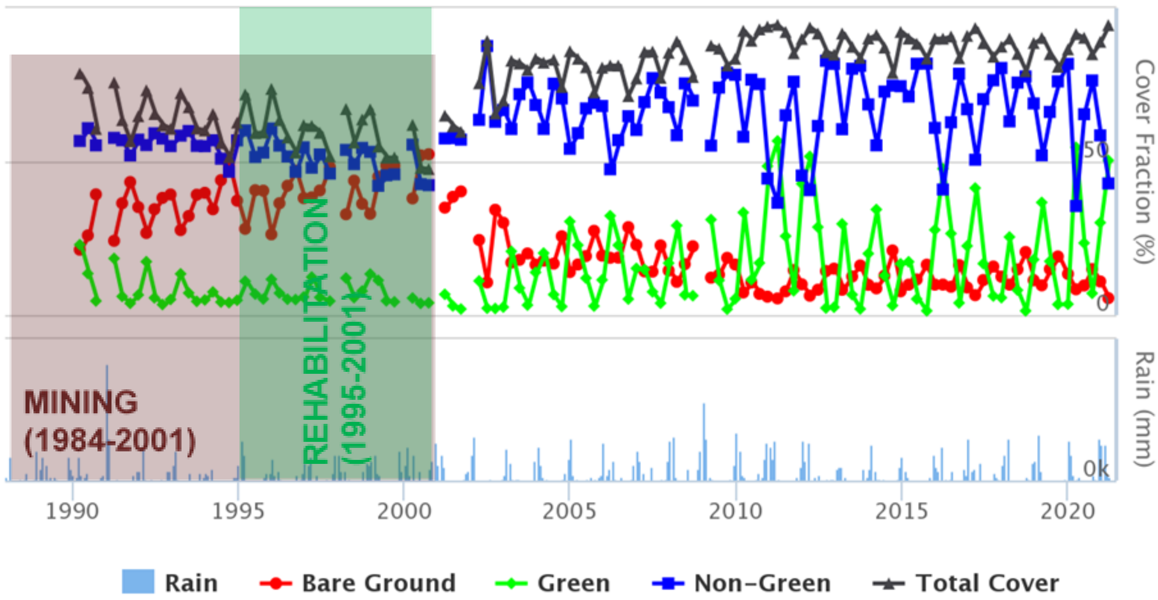


Figure 18: Ground cover on waste rock dump since 2001 (CSIRO, 2021)

Figure 19: Good density and diversity of revegetation cover on waste rock dump

(a) (b)

Figure 20: Treatment of side slope of waste rock dump: (a) partial over-dumping of oxide waste, and (b) wet season revegetation (green)

(a) (b)

Figure 21: Variable dry season revegetation of side slope of waste rock dump: (a) grasses on limited oxide waste, and (b) well-treed oxide waste

3.1.4 Rehabilitation of surface tailings storage facility

The Kidston tailings contained up to 1.5% sulfur, which was concentrated along tailings streams on the surface tailings storage facility during deposition, covering perhaps 10% of the tailings beach. The sulfur was largely neutralised by the alkaline process water (being a highly alkaline cyanide process), supplemented by the addition of lime along the final tailings streams to neutralise concentrated sulfur. The upper exposed layer of tailings oxidised and the oxidation products were largely leached by rainfall infiltration, resulting in a slightly alkaline pH, and rendering the tailings surface suited to direct revegetation with the addition of fertiliser and initial irrigation. The tailings also have a relatively low permeability. Both the low permeability of the tailings and the revegetation serve to limit the net percolation of rainfall.

The pump-back of seepage from the surface tailings storage facility to the pits provides an indicator of the seepage rate from the facility, and increases with rainfall totals, although it will be somewhat lagged in time.

Mean annual seepage from the tailings storage facility is estimated from pumping records to be up to 2.9% of rainfall incident on the total 414ha catchment (at 3.0 L/s).

Mulligan et al. (2006) reported on direct revegetation trials on tailings from 1998, and monitoring of the direct revegetation of the tailings from 2001 to 2005, which demonstrated progression towards a sustainable native plant community, achieving almost 70% revegetation cover and less than 15% bare ground. There was more diversity of shrubs and trees on the revegetated tailings than in the surrounding grazed land, which had been subjected to periodic burning to promote pasture grass resulting in a dominance of ironbark trees (Figure 22).

(a) (b)

Figure 22: Revegetation on tailings (a) versus natural regeneration (b)

3.1.5 Solar farm on surface tailings storage facility

Genex Power Limited purchased the Kidston Mine site in 2016, with the aim of converting it to a renewable energy/battery hub, taking advantage of the mined landforms present, including the flat top of the surface tailings storage facility, well-suited to the development of a Solar Farm.

In late 2017, Genex completed the construction of a 50 MW (AC, 63 MW DC) Solar Farm at a total cost of $124 million, over a large part of the near-flat Kidston tailings storage facility. The project required the removal of trees and shrubs, while the original seeding and planting of high proportions of introduced grasses and legumes persists beneath the rotating solar panels, and is regularly slashed (Figure 23). The grasses and legumes control dust off the underlying tailings, continuing to satisfy this key rehabilitation requirement.

The project (https://genexpower.com.au/50mw-kidston-solar-project) has 540,000 solar panels operating on a single axis tracking system with an anticipated project life of 30 years, and takes advantage of the highest solar radiation zone in Australia. It feeds power to the National Electricity Market via the existing Ergon Energy 132 kV transmission line that previously fed power to the Kidston Mine. The project generates up to 145,000 MWh/year, powering up to 26,000 homes, and offsets up to 120,000 t of CO_2/year.

(a)

(b)

Figure 23: Genex Solar Farm on Kidston tailings storage facility: (a) aerial view, and (b) rotating solar panels and underlying grass and legume cover

3.1.6 Pumped storage hydro project under construction

The Genex Pumped Storage Hydro Project utilising the two pits at Kidston will be the first pumped hydro project in Australia for over 40 years, the first to be developed by the private sector and the third largest electricity storage device in the country (https://genexpower.com.au/250mw-kidston-pumped-storage-hydro-project; Figure 24). Construction of the project commenced in May 2021, will create up to 900 direct jobs, and is planned to be completed in late 2024 and commissioned in early 2025, for a total cost of $777 million. The project will feed up to 250 MW into the approximately 7,000 MW Queensland sector of the National Electricity Market via a new transmission line. Over its 8-hour daily generation duration, it will have a storage capacity of 2,000 MWh. It will include two 125 MW reversible turbines in an underground cavern, with a start-up time of <30s, driven by a head of 181 to 218m from the upper reservoir above the turbines.

The greatly enlarged Wises Pit storage will serve as the upper reservoir, and Eldridge Pit as the lower storage reservoir. The expansion of the upper reservoir is need to maintain an adequate head above the turbines. The sides of the expanded Wises Pit will be lined with a geomembrane to limit seepage, while the underlying natural ground and pit walls are tight and of very low permeability. The nearby Copperfield Dam, which previously delivered water the Kidston Mine and continues to supply water for local cattle grazing, will provide up to 30% make-up water to replace that lost to evaporation from the enlarged upper reservoir. The below ground infrastructure of Genex Pumped Storage Hydro Project at Kidston is shown in Figure 25 (AECOM, 2018).

Eldridge Pit will receive all tailings storage facility and waste rock seepage pump-back in the future, leading to a minor decline in its water quality. The water quality in Wises Pit is expected to improve with the operation of the Pumped Storage Hydro, due to initial mixing with the currently better quality Eldridge Pit water, and ongoing dilution by fresh water from the Copperfield Dam.

Figure 24: Plan view of Genex Pumped Storage Hydro Project at Kidston

3.1.7 Sustainability of Genex Project at Kidston

The Genex Solar Farm and Pumped Storage Hydro Projects at Kidston have generated hundreds of construction jobs, and have long projected lives of at least 30 years and 80 years, respectively. The Solar Farm and Pumped Storage Hydro Projects, and other solar and wind generating projects planned by Genex, will require monitoring and maintenance for many decades, offering employment opportunities, and also providing the capability and resources to maintain the post-mining landforms at the site. This will focus primarily on maintaining the seepage collection ponds and pump-back system (which will be to Eldridge Pit). The repurposing of the Kidston site and its occupation by Genex ensures ongoing regional benefit, at the same time as ensuring the ongoing safe, stable and non-polluting status of the mine waste facilities at the site.

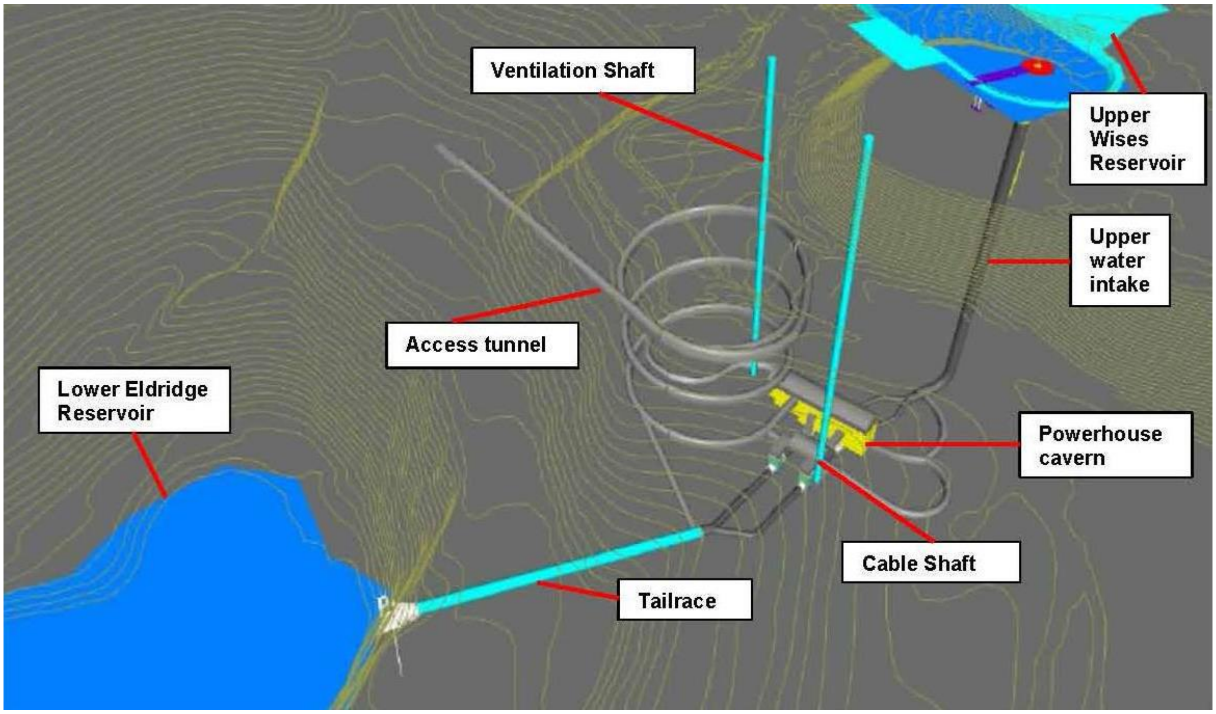


Figure 25: Below ground infrastructure of Genex Pumped Storage Hydro Project at Kidston

3.2 New Century Resources, North Queensland

The focus of this section is the reprocessing of the stored tailings for zinc recovery, and disposing of the residual tailings in-pit to be below the final pit water level, with all tailings removed from the tailings storage facility so that it will not require rehabilitation. A decision has not yet been made about the tailings and water storage dams.

Figure 26 shows a Google Earth image of the Century Zinc Mine site, which is now owned by New Century Resources, located 250km north-west of Mount Isa in North Queensland. Century Mine, previously owned and operated by MMG Limited, mined a large single open pit to August 2015. Apart from the ore, which graded up to 9% zinc, the two main waste rock types excavated from the pit were dolomite (referred to by mine personnel as limestone, with ANC and white in color), and shale (NAF and black in color, making it readily discernable from the limestone). The waste rock was end-dumped in three surface waste rock dumps (WRDs), with some of the shale backfilled into the completed part of the pit over the latter period of mining. The surface tailings storage facility ultimately covered an area of 360ha, not including the adjoining water storage dam having a similar area. The production of zinc concentrate from Century Mine was among the top three worldwide.

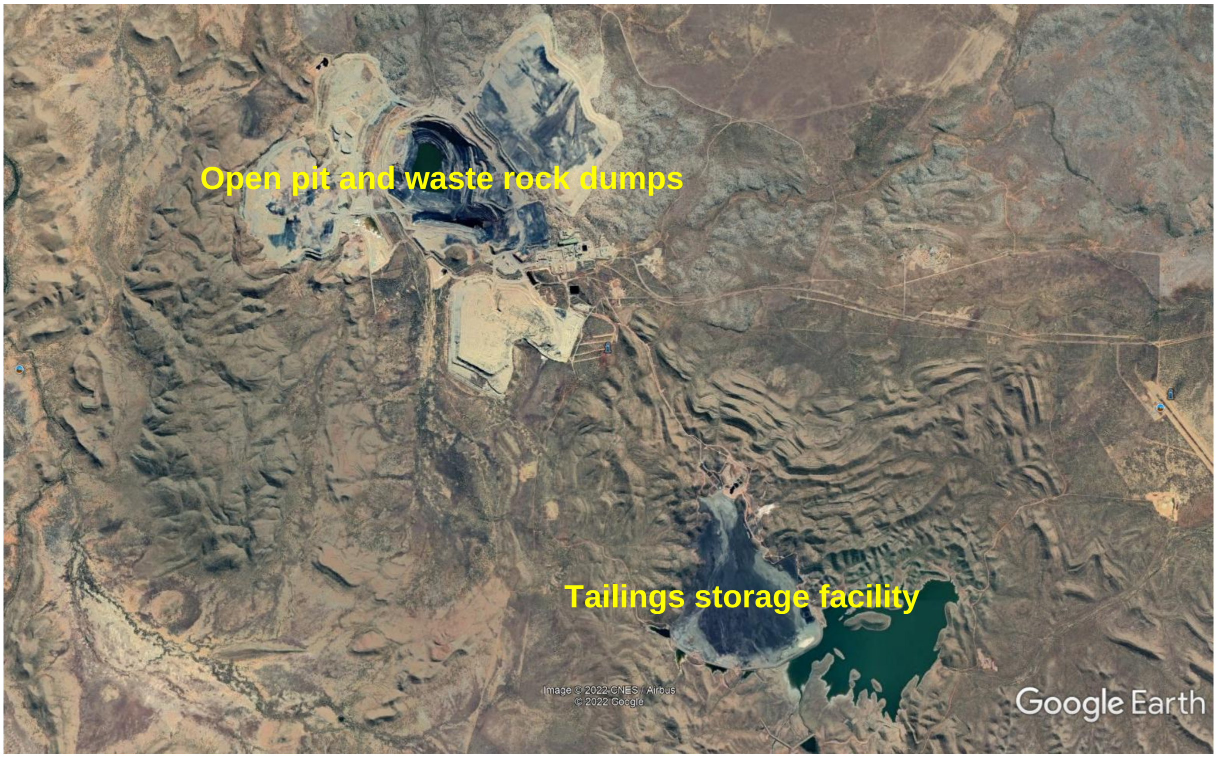


Figure 26: Google Earth image of Century Zinc Mine (June 2018)

Figure 27: Google Earth image of Century Zinc Mine tailings storage facility (June 2018)

3.2.1 Climatic setting

Century Mine is located in a dry climatic region, with a mean annual rainfall of 544mm, falling predominantly during the 4 months from December to March, and the average number of days of rain/year is 59 days, or only 16% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 300mm and 1,300mm, respectively, with up to 650mm recorded in a single month (January). The site climate is strongly net evaporative on average.

3.2.2 Remining and reprocessing tailings

New Century Resources commenced reprocessing zinc from the existing tailings in August 2018 and expects to have reprocessed all of the tailings by 2023/24, leaving no tailings in the tailings storage facility to be rehabilitated. The existing tailings in the Century Mine tailings storage facility contains up to 3% zinc and are being remined using a water monitor to re-slurry the tailings, which are directed via a channel to a sump from which they are pumped to the existing processing plant for reprocessing. Reprocessing recovers up to half the residual zinc, and the reprocessed tailings are deposited in the completed open pit, where they will ultimately be covered by pit water as it recovers. The production of zinc from the tailings ranks New Century Resources about the tenth largest producer of zinc concentrate worldwide.

The tailings storage facility footprint will have all of the tailings removed, plus any contaminated soil underlying the tailings, leaving no rehabilitation liability other than deciding what to do with the tailings and water storage dams. Both could potentially become water storages for ongoing cattle watering.

3.3 New Acland Coal Mine, South-East Queensland

The focus of this section is the rehabilitation of the surface and in-pit tailings storage facilities at New Acland Coal Mine, with some commentary on the progressive backfilling with spoil of the mined sections of the open pit. The rehabilitation of the site has allowed grazing to return, providing yields equal to or better than that achieved prior to mining.

Figure 28 shows a series of Google Earth images of the New Acland Coal Mine going back in time. New Acland Coal Mine is located in the Walloon Coal Measures, about 10km north of Oakey on the Darling Downs of South-East Queensland. Mining is by open cut, and much of the pit is progressively backfilled with spoil as mining proceeds, as shown in Figure 28.

(a) (b)

(c)

(d)

(e)

(f)

(g) (h)

Figure 28: Google Earth images of New Acland Mine going back in time: (a) February 2022, (b) January 2019, (c) December 2017, (d) September 2016, (e) February 2016, (f) April 2013, (g) September 2009, and (h) February 2004

3.3.1 Climatic setting

New Acland Mine is located in a sub-tropical climatic region, with a summer-dominated but distributed mean annual rainfall of 615mm, and the average number of days of rain/year is 80 days, or only 22% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 170mm and 900mm, respectively, with up to 304mm recorded in a single month (December). The site climate is strongly net evaporative on average.

3.3.2 Capping surface tailings storage facility

Figure 28 (g) also shows the surface tailings storage facility, which was capped and largely revegetated by December 2017 (as seen in Figure 28 (c)), and the first of four in-pit tailings storage facilities to the south, which were progressively capped and revegetated.

Williams and King (2016) described the capping of the New Acland surface tailings storage facility. The completed, conventional, surface slurried coal tailings storage facility required capping to facilitate rehabilitation for grazing purposes. The facility had been closed for some years and the upper part of the tailings beach was well-desiccated on the surface, but this extended to only about 0.6m depth, with the effect dropping off exponentially to that depth. It had previously been loaded with spoil, which had caused “bow-waving” of the tailings as they remoulded under the imposed weight of spoil and engaged the softer tailings underlying the surface crust. Bow-waving causes the tailings to “remould”, accompanied by a sudden reduction of strength of about 50% (at depth) to 70% (within the crust). Intermittent residual ponds covered the low areas of the facility with the extent of ponding varying with rainfall.

Prior to the commencement of capping, the tailings were tested for their strength profiles with depth using a field shear vane, the results of which were used to assess the safe trafficking of the D6 Swamp Dozer and placement of the initial capping layer. Both the peak and remoulded vane shear strengths were tested, the former representing small-strain loading and the latter representing bow-waving. An initial 1m thick capping layer of “free-draining” coarse reject (finer than a nominal 50mm) was placed using a D6 Swamp Dozer, slowly and over a broad front to prevent bow-waving and allow the loaded tailings to drain and strengthen before the fill was advanced. Capping commenced from the strongest, highest elevation of the tailings beach, and extended towards the ponds. As the capping progressed, further vane shear testing was carried out to assess the shear strength of the tailings beneath and beyond the capping layer, and the strength gain over time in the already covered tailings, which enabled further capping material to be safely placed.

The loading imposed by the D6 dozer was equivalent to about a 1m thickness of fill, and drainage over several weeks of the loaded tailings under the weight of the fill resulted in a strength gain in the tailings of about 10kPa (equivalent to the loading from about 0.5 m of fill), which allowed the filling to be advanced. Once the initial 1m of fill covered the entire tailings footprint, the tailings were “contained” and further thickness of fill could be placed. The initial capping was followed by the placement of 2 to 3 m thickness of coarse reject or spoil and topsoiling, using a D9 Dozer, and revegetation with pasture grasses to achieve the agreed post-mining grazing land use.

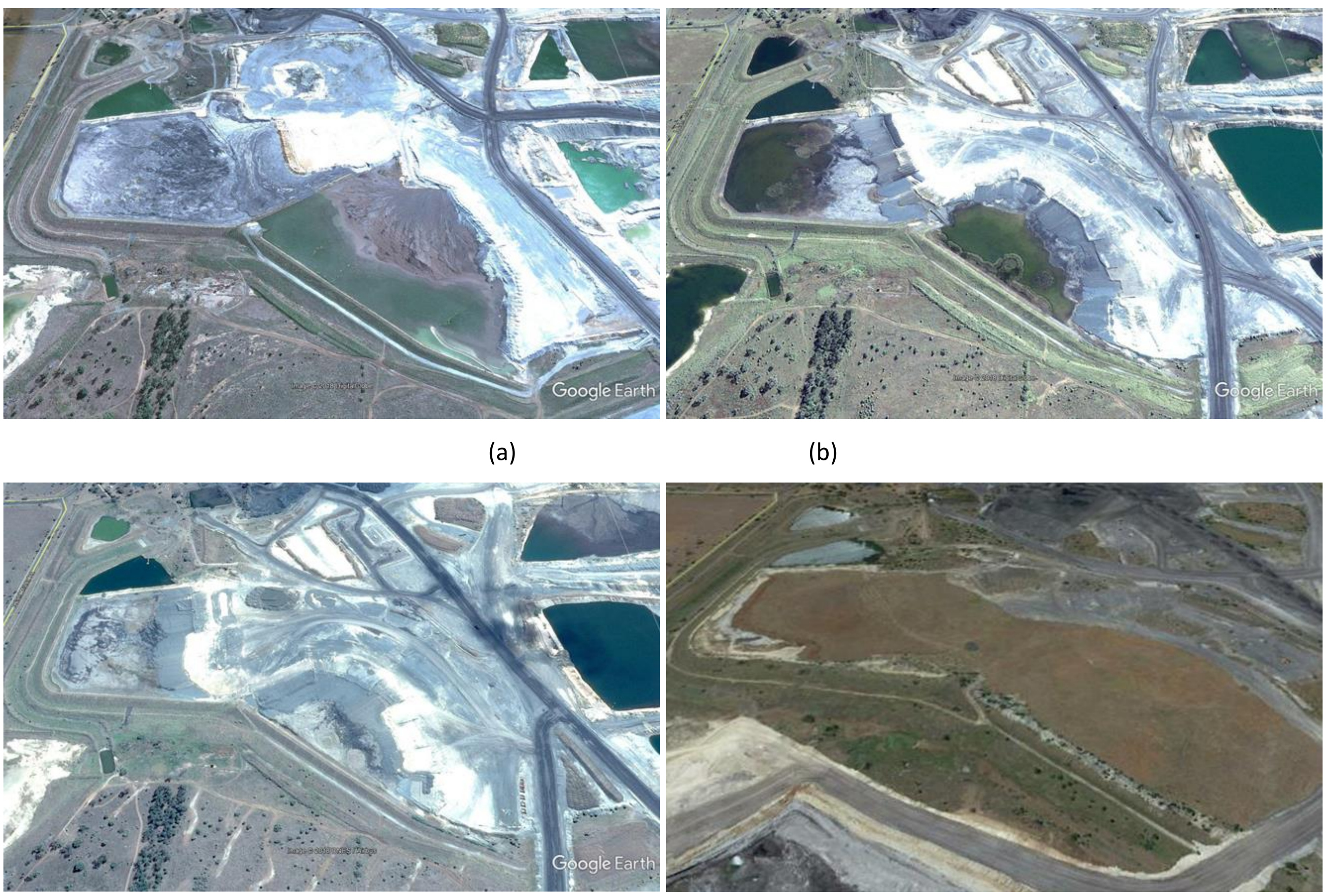
Capping of the New Acland surface tailings storage facility commenced in late 2009 and was completed and largely revegetated by December 2017. Figure 29 shows the start of pushing by D6 Swamp Dozer the initial 1m thick capping layer of coarse reject over the upper tailings beach. Figure 30 shows the observations of placing the initial capping layer, which were used to prevent bow-waving, and to safely direct the rate and advancement of initial capping. Placing the 1m thick initial capping led to a rise in the water table from about 1m depth to the surface, followed by hydraulic fracturing of the less permeable unsaturated surface crust to allow drainage from the more permeable saturated tailings at depth, and the initiation of bow-waving signaling the limit of safe capping at that location.

Figure 29: Start of pushing by D6 Swamp Dozer initial 1m thick capping layer of coarse reject over upper tailings beach

(a) (b) (c)

Figure 30: Impact of initial capping, showing: (a) rise in the water table to surface, (b) hydraulic fracturing of surface crust, and (c) initiation of bow-waving

Figure 31 shows a series of Google Earth images of the progressive capping of the New Acland surface tailings storage facility.



(a) (b)

(c) (d)

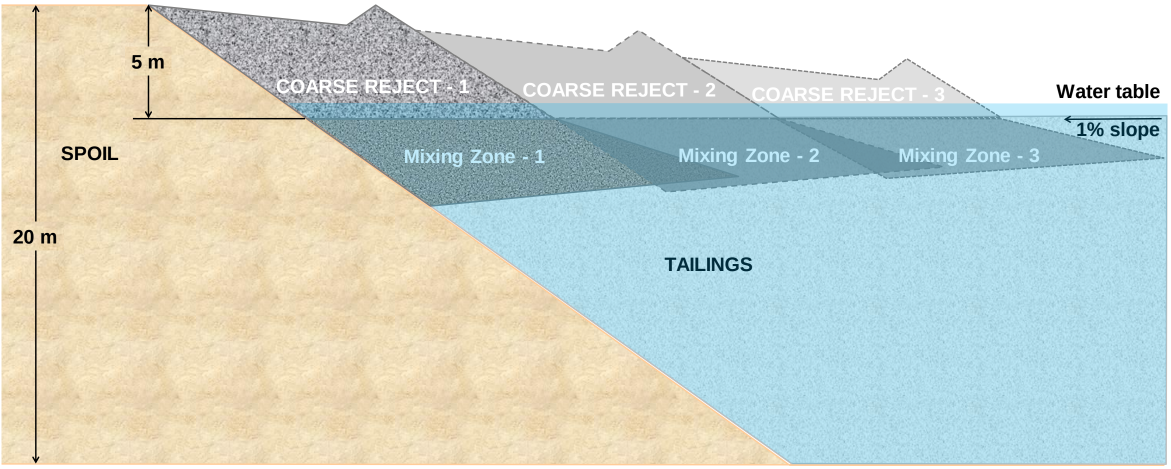
Figure 31: Google Earth images of progressive capping of New Acland surface tailings storage facility: (a) before capping in August 2009, (b) progress of capping by April 2013, (c) progress of capping by March 2014, and (d) completed capping in December 2017

3.3.3 Capping in-pit tailings storage facility

Wet and soft tailings, such as those deposited in-pit, may be "capped" by hydraulic placement or by end-dumping of free-draining and durable coarse material. Hydraulic placement would involve the pumping of coarse materials such as coarse reject, forming a steep beach of about 1 vertically in 10 horizontally, and progressively moving the discharge pipeline out over the steep beach to complete the cover. Figure 32 (a) shows the coarse reject upper beach that forms on the pumped co-disposal of coal washery wastes (coarse reject and tailings). A similar steep beach would form if coarse reject only were pumped.

End-dumping of spoil or coarse material, such as waste rock, spoil or coarse reject, off a tip-head, could also form a cap over wet and soft in-pit tailings, as shown schematically in Figure 32 (b), similar to end-dumping in water. The coarse material would displace water and tailings solids within the mixing zone, loading the tailings below, with clean coarse material above. End-dumping could be progressed out from the tip-head. The shear strength profile with depth of tailings always maintained under water is zero at the tailings surface and increases linearly with depth at a rate dependent on the specific gravity of the tailings solids and the extent to which the tailings are fully normally-consolidated. For coal mine tailings with a specific gravity of less than 2.0, their normally-consolidated shear strength would increase with depth at a rate of about 0.8 kPa/m depth. For typical metalliferous tailings, with a specific gravity of 2.8, their normally-consolidated shear strength would increase with depth at a rate of about 1.2 kPa/m depth. This shear strength would provide some bearing capacity for the end-dumped coarse material, which would progress deeper into the tailings as more mass of coarse material is added.

(a)



(b)

Figure 32: Capping wet and soft tailings, by: (a) hydraulic placement of coarse material, and (b) end-dumping of coarse material

The in-pit tailings storage facilities at New Acland were capped by end-dumping coarse reject or spoil from the highwall of the pit and pushing similar capping material from the upper tailings beach. Figure 31 shows a series of Google Earth images of the progressive capping of the first New Acland in-pit tailings storage facility. It can be seen that the end-dumping from the left-hand highwall of the pit was able to continue to progress, while the capping from the upper beach became stalled due to the limited strength and bearing capacity further down the beach. The capped in-pit tailings storage facility was revegetated with pasture grasses to achieve the agreed post-mining grazing land use.

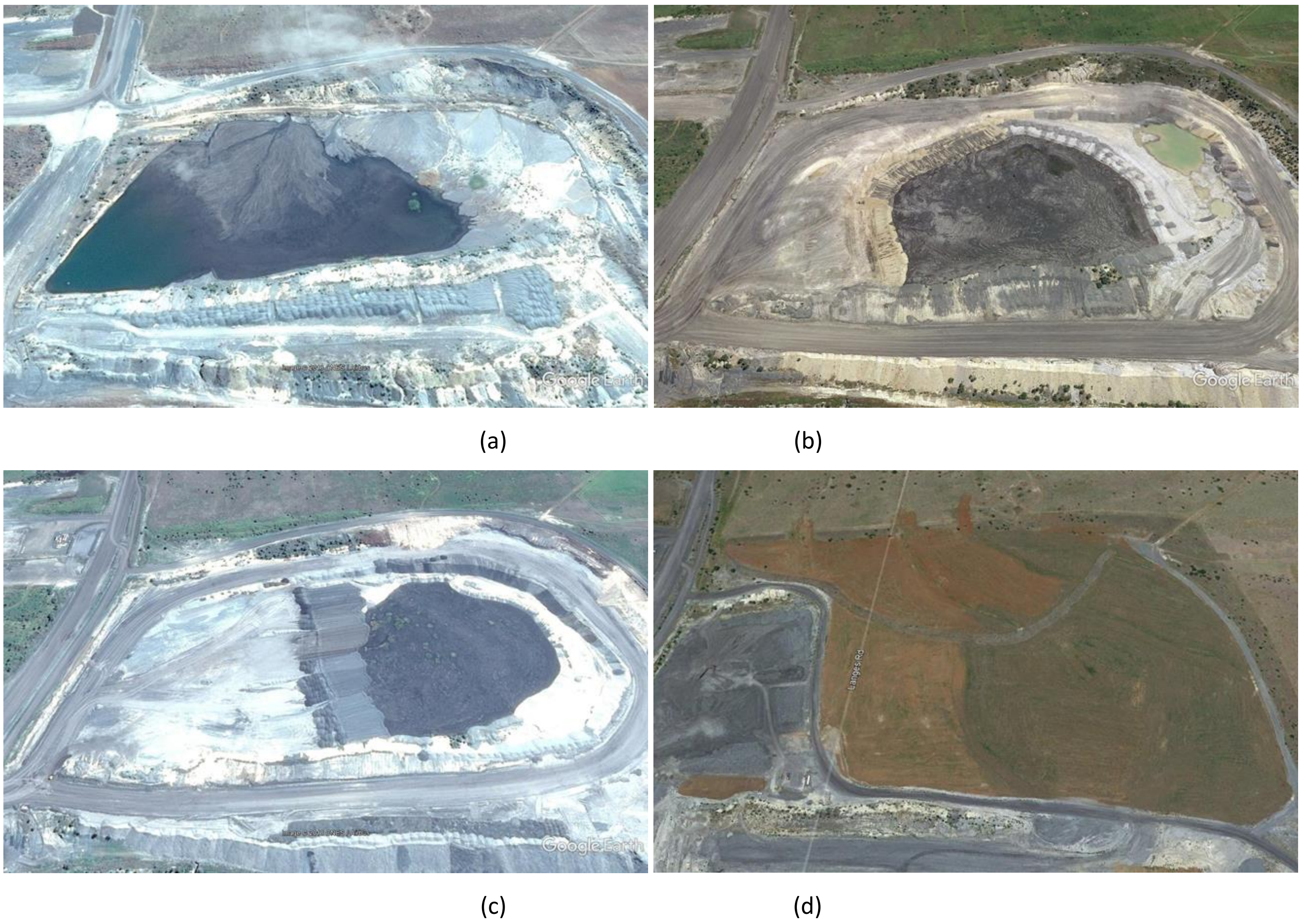


Figure 33: Google Earth images of progressive capping of first New Acland in-pit tailings storage facility: (a) before capping in March 2014, (b) progress of capping by February 2016, (c) progress of capping by September 2016, and (d) completed capping in December 2017

3.4 McArthur River Mine, Northern Territory

The focus of this section is the reshaping, covering and changed operation of the North Overburden Emplacement Facility to mitigate spontaneous combustion and the generation of noxious SO_2, CO and CO_2, and sulfate-contaminated seepage from the facility, to restore the mine's social, environmental and financial licenses to operate. In the future, the mine proposes reprocessing of the stored tailings and disposing of the residual tailings in-pit to be below the final pit water level.

Figure 34 shows a series of Google Earth images of the McArthur River Mine North Overburden Emplacement Facility going back in time. McArthur River Mine is located on one of the world's largest deposits of zinc and lead, in a remote area about 970km south-east of Darwin in the Northern Territory. Initially an underground mine, McArthur River Mine converted to open pit mining in 2006.

(a) (b)

(c)

Figure 34: Google Earth images of McArthur River Mine North Overburden Emplacement Facility going back in time: (a) June 2018, (b) July 2013, and (c) June 2010

3.4.1 Climatic setting

McArthur River Mine is located in a tropical climatic region, with a mean annual rainfall of 773mm, falling predominantly during the four months from December to March, and the average number of days of rain/year is 63 days, or only 17% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 294mm and 1,604mm, respectively, with up to 782mm recorded in a single month (January). The site climate is strongly net evaporative on average.

3.4.2 Oxidation of waste rock

The North Overburden Emplacement Facility suffered from oxidation of sulfidic waste rock, leading to "spontaneous combustion" due to it being an exothermic reaction, the generation of noxious gases SO_2, CO and CO_2, and the production of acidic seepage from the facility, which was collected in lined ponds around the toe. Figure 35 to Figure 38 show photographs taken of the North Overburden Emplacement Facility in August 2015. Figure 35 shows examples of oxidation of potentially acid forming waste rock in the facility on exposure to oxygen and moisture.

Figure 35: Oxidation of sulfidic waste rock exposed on the North Overburden Emplacement Facility

3.4.3 Initial capping of North Overburden Emplacement Facility

In an attempt to reduce spontaneous combustion of sulfidic waste rock in the North Overburden Emplacement Facility, compacted layers were applied to the dump top and to the side flattened side slopes of the dump. While successful in reducing spontaneous combustion, the relatively thin compacted layers did not eliminate the problem, nor the generation of noxious gases. Figure 36 and Figure 37 show, respectively, the breakthrough of a compacted rock layer and a compacted clay layer, due to spontaneous combustion of thinly-covered sulfidic waste rock. The oxidation reaction produces secondary minerals that take up more volume that the original rock, leading to heave and surface cracking. Overall, such a dump can swell over a meter.

Figure 38 shows large-scale capping of the North Overburden Emplacement Facility, which again was only partially successful in reducing spontaneous combustion, and a view down to a seepage collection pond at the toe, and Figure 39 shows the view from the North Overburden Emplacement Facility towards the nearby culturally significant Barrumundi Dreaming landform.

Figure 36: Breakthrough of a compacted rock layer due to spontaneous combustion of thinly-covered sulfidic waste rock

(a) (b)

Figure 37: Capping flattened dump slopes with compacted clay to mitigate spontaneous combustion of underlying waste rock, showing: (a) flattening and capping of smoldering waste rock, and (b) breakthrough of a compacted clay layer

(a)

(b)

Figure 38: View of North Overburden Emplacement Facility, showing: (a) large-scale capping, and (b) view down to a seepage collection pond at toe

Figure 39: View towards nearby culturally significant Barrumundi Dreaming landform

3.4.4 Progressive rehabilitation of North Overburden Emplacement Facility

In 2012, McArthur River Mine prepared an Overburden Emplacement Facility Management Plan (MRM, 2012) and in 2017 a Supplementary Environmental Impact Statement submitted to the Northern Territory Environment Protection Authority (MRM, 2017). The Management Plan proposed alternative covers for the slopes of the North Overburden Emplacement Facility flattened to 5 horizontal to 1 vertical, depending on whether or not they were underlain by PAF waste rock or NAF waste rock, as shown in Figure 40. The final landform of the North Overburden Emplacement Facility proposed in 2012 is shown in Figure 41, including its shedding cover, and highlighting its proximity to the Barramundi Dreaming landform.

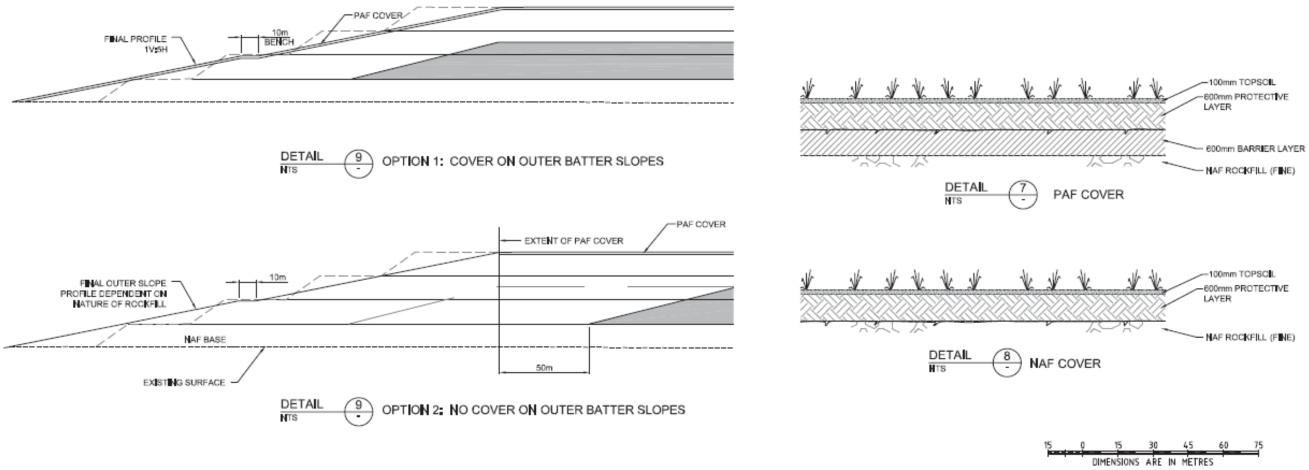


Figure 40: Alternative covers for flattened slopes of North Overburden Emplacement Facility proposed in 2012

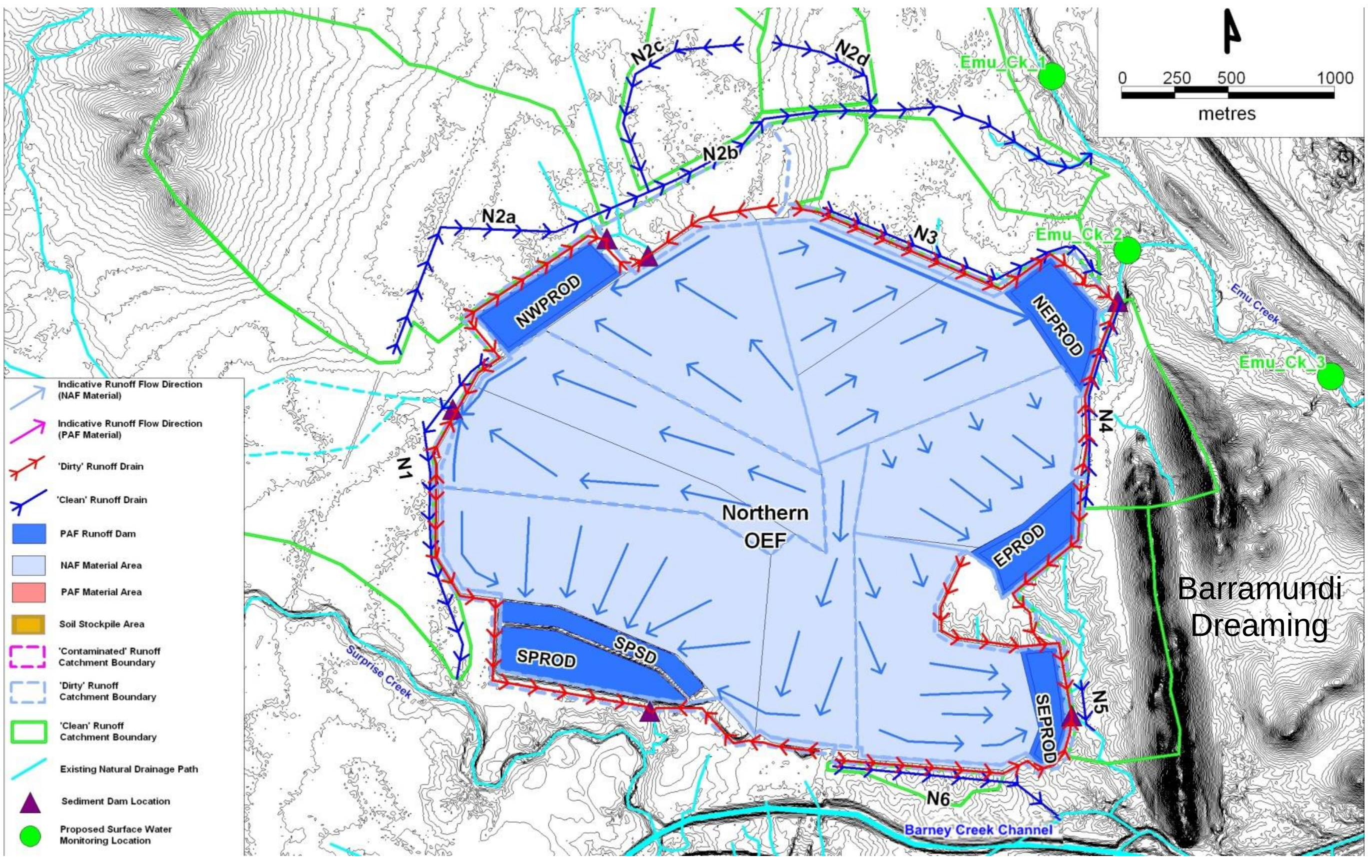


Figure 41: Final landform of North Overburden Emplacement Facility proposed in 2012

The 2012 cover strategy was revised in the 2017 Supplementary Environmental Impact Statement to that shown in Figure 42, with the most potentially acid-forming waste rock encapsulated well within the dump and, crucially, not located under the side slopes that are difficult to cap. The final slope profile was replaced with a concave shape that better matches natural slope profiles, driven by community expectations, and also reduces erosion.

The progressive rehabilitation of the North Overburden Emplacement Facility in accordance with the Supplementary Environmental Impact Statement is shown in photographs taken in April 2021 in Figure 43.

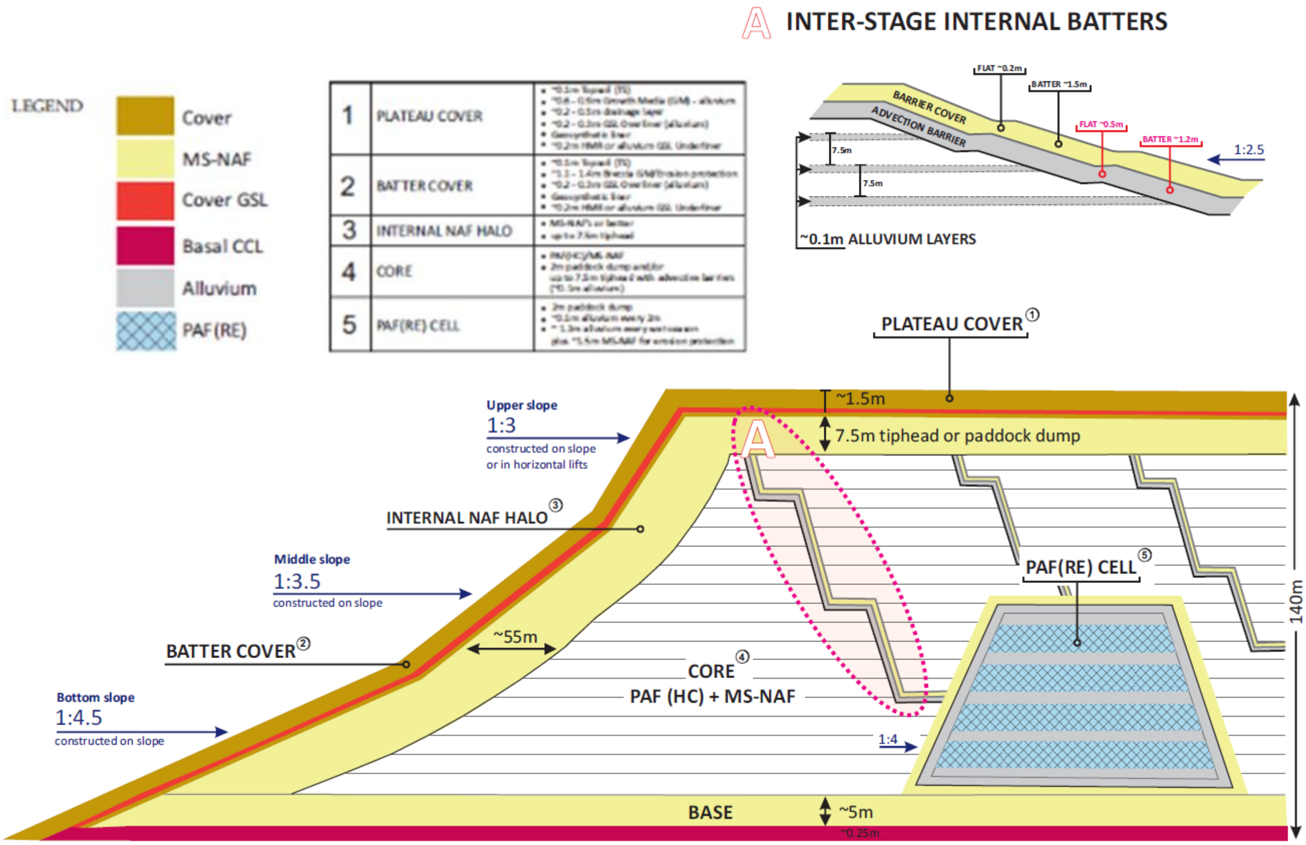


Figure 42: Revised North Overburden Emplacement Facility cross-section proposed in 2017

Figure 43: Progressive rehabilitation of North Overburden Emplacement Facility in accordance with Supplementary Environmental Impact Statement in April 2021

3.5 Hunter Valley Coal Mine, New South Wales

The focus of this section is the rehabilitation of the above-ground spoil piles at the Hunter Valley Bengalla Coal Mine aimed at providing the required visual buffer to the town of Muswellbrook that faces it, and to potentially achieve a post-mining grazing land use.

Figure 44 shows a series of Google Earth images going back in time of the open cut Bengalla Coal Mine, located in the Hunter Valley Coalfields of New South Wales, showing the visual bund facing Muswellbrook to the east.

(a) (b)

(c) (d)

(e) (f)

Figure 44: Google Earth images of Bengalla Coal Mine going back in time: (a) December 2021, (b) May 2020, (c) September 2018, (d) December 2015, (e) January 2014, and (f) January 2009, showing the visual bund facing Muswellbrook to the east

3.5.1 Climatic setting

Bengalla Coal Mine is located in a sub-tropical climatic region, with a summer-dominated but distributed mean annual rainfall of 613mm, and the average number of days of rain/year is 107 days, or 29% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 281mm and 981 mm, respectively, with up to 265mm recorded in a single month (November). The site climate is strongly net evaporative on average.

3.5.2 Bengalla Coal Mine Visual bund

Figure 45 and Figure 46 show photographs of the Bengalla Coal Mine visual bund facing Muswellbrook taken in September 2016 and February 2017, respectively. In Figure 45, the slope to the west (left) is yet to reshaped from angle of repose benches and revegetated to meet community expectations.

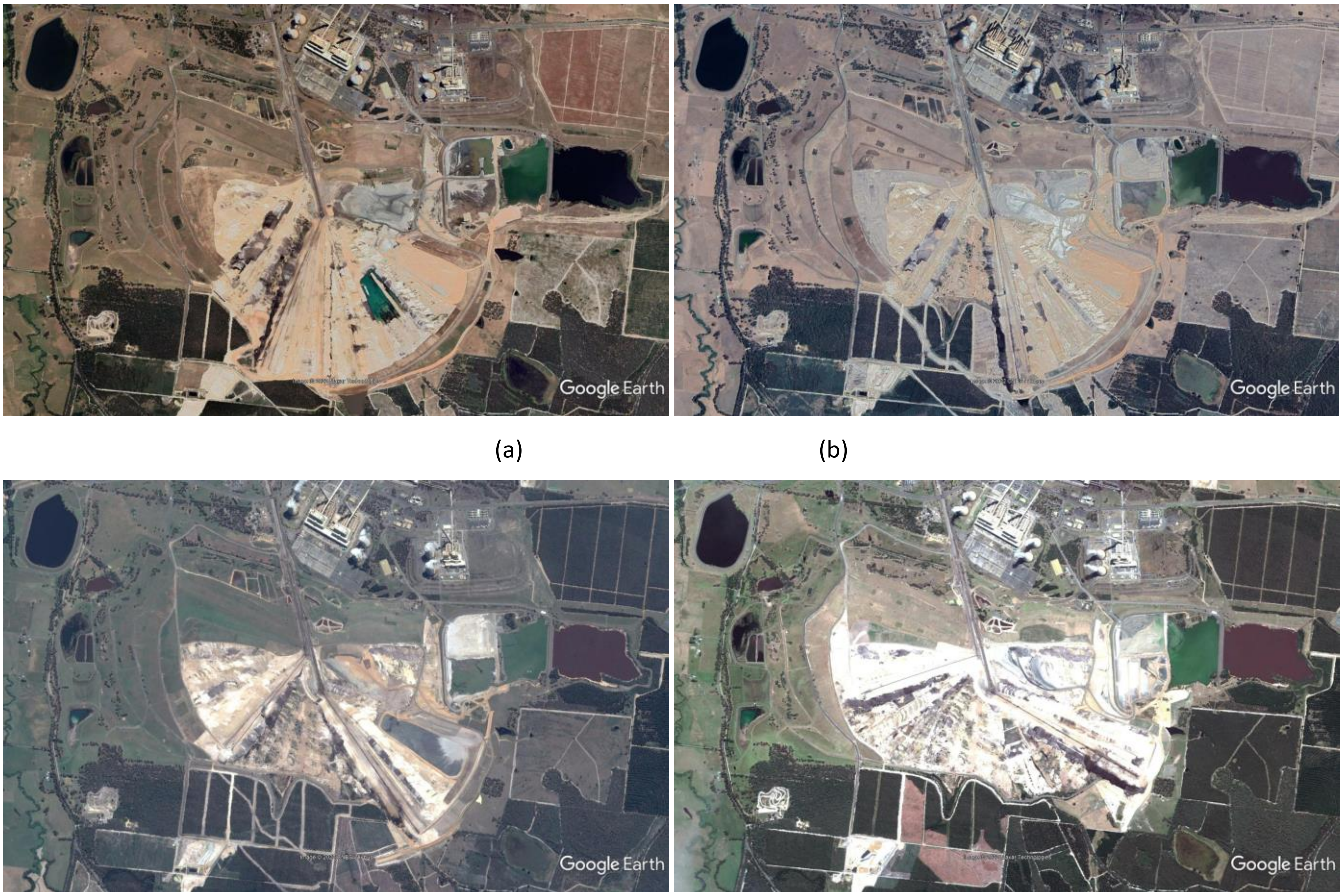
Figure 45: Photographs of Bengalla Coal Mine visual bund facing Muswellbrook taken in September 2016

Figure 46: Photographs of Bengalla Coal Mine visual bund facing Muswellbrook taken in February 2017

3.6 Latrobe Valley Mine, Victoria

The focus of this section is the progressive rehabilitation of the Latrobe Valley Loy Yang surface overburden dump and upper slopes of the open cut as mining progresses.

Figure 47 shows a series of Google Earth images going back in time of the surface overburden dump at Loy Yang Mine, located in the Latrobe Valley of Victoria. The mine is located to the north of the dump and rehabilitation has been focused on the northern slope of the dump because this is more fixed. There is less rehabilitation to the southern side of the dump in areas where it is still being expanded.



(a) (b)

(c) (d)

Figure 47: Google Earth images of Loy Yang Mine going back in time: (a) January 2022, (b) January 2019, (c) November 2015, and (d) January 2012

3.6.1 Climatic setting

The Latrobe Valley is located in a Mediterranean climatic region, with a winter-dominated but distributed mean annual rainfall of 737mm, and the average number of days of rain/year is 171 days, or 47% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 464mm and 947mm, respectively, with up to 203mm recorded in a single month (December). The site climate is net evaporative on average.

3.6.2 Overburden dump and open cut rehabilitation

Figure 48 shows the unrehabilitated expanding southern side of the Loy Yang overburden dump in June 2010.

Figure 48: View of unrehabilitated Loy Yang overburden dump in June 2010

The open cut at Loy Yang Mine is over 100m deep, as are the other open cut mines in the Latrobe Valley. The open cuts extend well below the regional groundwater level, and their stability is maintained only by ongoing extensive dewatering. Dewatering has also resulted in settlements of over 2m and differential settlements of the ground away from the pits as the effect diminishes with distance. If dewatering were to cease, the pits are expected to heave substantially, and would likely undergo slope instability. There is very limited backfill available, since the depth of overburden above the brown coal is limited, ruling out backfilling as an option. There is also insufficient water available to flood the pits sufficiently rapidly to avoid heave and slope instability, given that the dewatering pumps would no longer be effective. As a result, rehabilitation of the open cut at Loy Yang has been limited to treatment of the upper slopes.

Figure 49 shows rehabilitation and trial rehabilitation of the upper slopes of the Loy Yang open cut in June 2010. Figure 50 shows a view of the rehabilitated super-elevated overburden dump beyond Loy Yang open cut in October 2018.

Figure 49: Rehabilitated upper slopes and trial slope rehabilitation of Loy Yang open cut in June 2010

Figure 50: View of rehabilitated overburden dump beyond Loy Yang open cut in October 2018

3.7 Sovereign Hill, Victoria

The focus of this section is the successful repurposing of abandoned old gold mine workings for tourism, rather than on landform design and stability.

Sovereign Hill is a living museum presenting the story of Ballarat as a goldrush boomtown. Gold was discovered there in 1851, triggering the greatest alluvial gold rush the world has ever known. The sleepy pastoral settlement of Ballarat grew rapidly into a fine provincial city built on the wealth derived from its gold. Covering 15 ha of a former gold mining site, Sovereign Hill's Outdoor Museum brings the gold rushes to life through a living township with diggings, underground mines, costumed characters, coach rides and 1850s shops, trades, schools and dwellings. Sovereign Hill's Outdoor Museum opened on Sunday, 29 November 1970, born from a vision in the 1960s when community groups sought to preserve the city's vibrant goldrush heritage and the story of its impact on Australia.

Sovereign Hill has become an Australian tourism icon and a winner of major tourism awards, attracting 450,000 visitors annually. The Outdoor Museum enjoys international renown as a living museum featuring rare trades, working machinery and exhibits, costumed interpreters and visitor participation. Some 350 staff work to bring our goldrush story to life. They are supported by over 250 volunteers who help bring the Outdoor Museum to life and assist with curatorial work and tour guiding.

3.7.1 Climatic setting

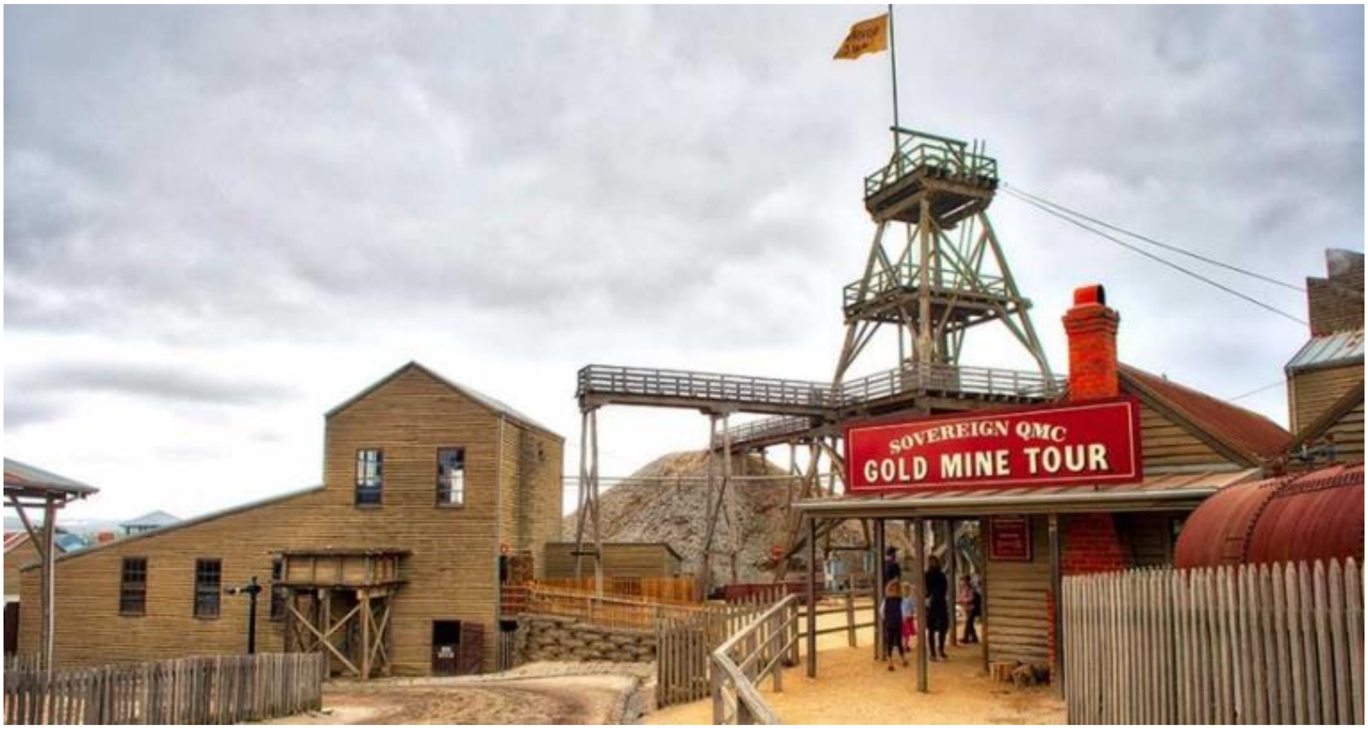
Sovereign Hill is located in a Mediterranean climatic region, with a winter-dominated but distributed mean annual rainfall of 687mm, and the average number of days of rain/year is 167 days, or 46% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 302mm and 995mm, respectively, with up to 240mm recorded in a single month (February). The site climate is net evaporative on average.

3.7.2 Images of Sovereign Hill Outdoor Museum

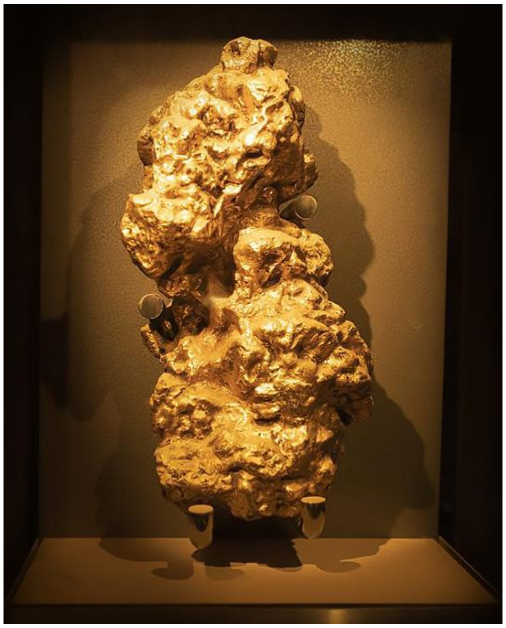
The second-largest gold nugget in the world, the "Welcome Nugget" was found on 9 June 1858 at Ballarat's Red Hill Mine, and is recreated in the Sovereign Hill Outdoor Museum. The Welcome Nugget weighed 69kg, (2,200 ounces) and was 99.2% pure gold. It was valued at about 10,596 pounds when found, and would be worth over $4 million in gold now, or far more as a specimen.

Main street of Sovereign Hill Outdoor Museum is a loose reconstruction of Main Street, Ballarat East, which was once the settlement's main street, consisting of timber buildings. The original Main Street was destroyed in a large fire during the 1860s and a more substantial town centre planned around Sturt and Lydiard Street in Ballarat West. Figure 51 shows images of the Sovereign Hill Outdoor Museum.

(a)



(b)



(c)

(d)

Figure 51: Images of Sovereign Hill Outdoor Museum, showing: (a) an aerial view, (b) Museum entry, (c) replica of Welcome Nugget, and (d) gold workings tourist attraction

3.8 Henty Gold Mine, West Coast of Tasmania

The focus of this section is reporting on the success of a combined peat and water cover on sulfidic tailings produced by the underground Henty Gold Mine to limit their oxidation and the generation of acid and metalliferous drainage on the wet West Coast of Tasmania.

Figure 52 shows a Google Earth image of the Henty Gold Mine tailings storage facilities in November 2018. The covered old tailings storage facility is in the top left-hand corner of the image.

Figure 52: Google Earth images of Henty Gold Mine tailings storage facilities (November 2018)

3.8.1 Climatic setting

Henty Gold Mine is located in a temperate, wet maritime climatic region, with a winter-dominated but distributed mean annual rainfall of 1,563mm, and the average number of days of rain/year is a high 243 days, or 67% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 1,196mm and 2,024mm, respectively, with up to 352mm recorded in a single month (June). The site climate has a net positive water balance for most of the year, apart from February.

3.8.2 Peat and water cover on sulfidic tailings at Henty Gold Mine

Water covers are recognised as a preferred method of controlling oxidation of sulfides in tailings and waste rock, in climates where the availability of water is adequate to maintain continuous saturation. However, there is a resistance to this method for long-term, low maintenance closure of these storage facilities due to the perceived risks associated with water storage dams.

Tailings dams are closely regulated by Government in most jurisdictions and require management systems appropriate to the hazard rating of the structure. This is now determined in Australia using the ANCOLD (2019) Tailings Guidelines, relating to the consequences of failure. For closure, ANCOLD (2019) now requires design for an Extreme Dam Failure Consequence Category, involving 1 in 10,000-year flood and earthquake loadings.

For Henty, Brett (2009) describes a combined peat and water cover over the old tailings storage facility. The concept was to expand the perimeter of the tailings storage facility by reconstructing a natural peat cover, adding to the stability of the tailings dam, and containing a water cover within the interior of the facility. The wet climate of the site ensures that the peat remains saturated, which, together with the water cover, effectively excludes oxygen ingress into the underlying sulfidic tailings, which remain saturated. A spillway was incorporated capable of passing the probable maximum flood, while ensuring that the saturated peat and water cover were maintained. The performance of the cover has been assessed over time to have mitigated acidic seepage from the facility. Photographs of the cover, taken in April 2008, are shown in Figure 53.

Figure 53: Photographs of peat and water cover over old tailings storage facility at Henty Gold the Google Earth images of Henty Gold Mine tailings storage facilities taken in April 2008

3.9 Kanmantoo Copper Mine, South Australia

The focus of this section is reporting on the rehabilitation of the combined surface tailings storage facility and waste rock dump, and the proposed pumped storage hydro use of the pit in collaboration with AGL.

Figure 54 shows a series of Google Earth images going back in time of Kanmantoo Copper Mine, located in the Adelaide Hills in South Australia.

Figure 54: Google Earth images of Kanmantoo Copper Mine going back in time: (a) January 2019, (b) January 2017, (c) January 2015, (d) February 2013, (e) November 2010, and (f) December 2003

3.9.1 Climatic setting

Kanmantoo Copper Mine is located in a Mediterranean climatic region, with a winter-dominated but distributed mean annual rainfall of 764mm, and the average number of days of rain/year is 138 days, or 38% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 382mm and 1,293mm respectively, with up to 271mm recorded in a single month (May). The site climate is net evaporative on average.

3.9.2 Rehabilitation of combined surface tailings storage facility and waste rock dump

The rehabilitation of the Kanmantoo Copper Mine involved the combining of the tailings storage facility (TSF, but excluding the old tailings dam, OTD) and the 1970s waste rock dump (to the right in Figure 55) into an integrated waste landform (IWL), as shown in Figure 55 and Figure 56. The integrated waste landform is being encapsulated with non-acid forming waste rock, which is then covered with a rocky growth medium and revegetated. Non-acid forming waste rock will also cover the ultimate top of the integrated waste landform, which will then be covered with a rocky growth medium and revegetated. All acidic seepage will be directed to the seepage collection pond, with the expectation that as the tailings and waste rock drain down following closure, the seepage rate will decrease.

Figure 55: Proposed integrated waste landform at Kanmantoo Copper Mine


(a) (b)


(c) (d)


(e) (f)

(g) (h)

Figure 56: Photographs of integrated waste landform under construction at Kanmantoo Copper Mine in July 2019, showing: (a) existing tailings storage facility, (b) reshaping of IWL, (c), (d) and (e) revegetation of lower flatter slope of IWL, (f) seepage collection pond, (g) surrounding natural landform and vegetation, and (h) final IWL slope

3.10 Collie Coal Mine, South-West Western Australia

The focus of this section is reporting on the success of creating a pit lake in an open cut at the Collie Coal Mine for recreational and/or fishery use, and plans to extend this successful repurposing to other pits, possibly including pumped storage hydro use.

The Collie Coal Basin, located approximately 160 km south of Perth, is the centre of the coal mining industry in Western Australia (McCullough, 2021). More than 100 years of coal mining around Collie has resulted in 13 significant pit lakes with differing water quality and extent of rehabilitation. All pit lakes are acidic due to moderate acid and metalliferous drainage from the low sulfide spoil and overburden surrounding them. The most significant of the pit lakes is Lake Kepwari, which has been integrated into the Collie River South Branch. Figure 57 shows two Google Earth images of Lake Kepwari over time.

Contoured spoil is seen in Figure 57 (a) to the west and east of Lake Kepwari, which continues to erode into the pit lake. In Figure 57 (b), the western slope has been reprofiled, eliminating the contour banks, in an effort to reduce erosion.

(a)

(b)

Figure 57: Google Earth images of Collie Coal Mine Lake Kepwari going back in time: (a) January 2022, and (b) October 2013

3.10.1 Climatic setting

Collie Coal Mine is located in a Mediterranean climatic region, with a winter-dominated mean annual rainfall of 928mm, falling predominantly during the 5 months from May to September, and the average number of days of rain/year is 135 days, or 37% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 419mm and 1,467mm, respectively, with up to 474mm recorded in a single month (June). The site climate is net evaporative on average.

3.10.2 Rehabilitation of Collie Coal Mine Open Pit

To enable coal reserves beneath the original Collie River South Branch to be mined and to fill Lake Kepwari (which was estimated to take 100 years to fill naturally), the South Branch of the Collie River was diverted into Lake Kepwari to the north during the winters from 2002 to 2008, and an outlet spillway to the south controls the lake level (**Figure 58** (a)). Although the input of Collie River South Branch water initially raised the pH of Lake Kepwari to above 7, the pH then fell below 4 once river inflows ceased. This low pH and associated elevated concentrations of some metals and metalloids reduced water quality and restricted end use opportunities. However, the lake remained visually spectacular with extremely high transparency due to an absence of phytoplankton, restricted by low phosphorus due to the acidic water (**Figure 58** (b)).

Heavy rainfall in August 2011 led to the overtopping and erosion of the diversion channel into Lake Kepwari (**Figure 58** (c)). This unintentional flushing had the effect of substantially improving the water quality and ecosystem values of the lake, raising the pH from about 4 to about 7.5 and lowering the electrical conductivity from about 3,200 to about 2,200 mS/cm, by late 2018. This indicated that maintaining the lake as a flow-through system would likely be a sustainable closure strategy, and led in November 2018 to the relinquishment of Lake Kepwari. **Figure 58** (d) shows the boat ramp constructed to enable recreational use of Lake Kepwari.


(a) (b)


(c) (d)

Figure 58: Photographs of Lake Kepwari, showing: (a) outlet spillway, (b) overtopping of input diversion due to heavy rainfall in August 2011, (c) perimeter beach, and (b) boat ramp

3.11 Beenup Mineral Sands Mine, South-West Western Australia

The focus of this section is reporting on the success of rehabilitation of the Beenup Mineral Sands Mine through the creation of pit lakes.

Figure 59 shows a series of Google Earth images going back in time of the rehabilitation of the Beenup Mineral Sands Mine, located in South-West Western Australia, in which the mining voids remained as pit lakes.

Figure 59: Google Earth images of Beenup Minerals Sands Mine going back in time: (a) October 2018, (b) December 2016, and (c) February 2011

3.11.1 Climatic Setting

Beenup Mineral Sands Mine is located in a Mediterranean climatic region, with a winter-dominated mean annual rainfall of 955mm, falling predominantly during the 5 months from May to September, and the average number of days of rain/year is 180 days, or 49% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 531mm and 1,464mm, respectively, with up to 368mm recorded in a single month (June). The site climate is net evaporative on average.

3.11.2 Rehabilitation of Beenup Mineral Sands Mine

Mining at Beenup ceased in April 1999 (Figure 60 (a)) due to insufficient consolidation of the clay tailings, which impacted production. Sub-aqueous tailings deposition was necessary because they contained zones of pyritic soils with the potential to oxidise and form acid when exposed to air. At the time of closure, 335ha of land had been disturbed, including a 2.1km long dredge pond and a 40ha dam containing the initial volume of sand and clay excavated from the dredge pond. Two temporary dams were also constructed to contain clay fines. The total amount of water in the pond and storage dams at closure was estimated to be 5.5mm³.

The closure and rehabilitation of the former Beenup Minerals Sands Mine, following extensive community consultation focused on protecting the water quality of downstream river systems (BHP, 2018 and Norrish et al. 2019). The aim was to establish permanent wetlands surrounded by native vegetation that link with the Scott National Park (Figure 60 (b)). These wetlands receive water from and discharge to the surrounding creeks and rivers.

(a) (b)

Figure 60: Beenup Mineral Sands Mine, showing: (a) cessation of mining in 1999, and (b) completed rehabilitation in 2018

Rehabilitation of the site was largely completed in 2018 (Figure 61), although monitoring and inspection of spillways and other engineered structures continues. Dredge pond water was treated and used for irrigation. Pyrite soils were neutralisation and permanently saturated. Surface water drainage was reinstated to reflect the baseline qualities of nearby water systems. The resulting wetlands, established in collaboration with the Western Australian Botanic Gardens and Parks Authority, are now host to four declared rare flora species.

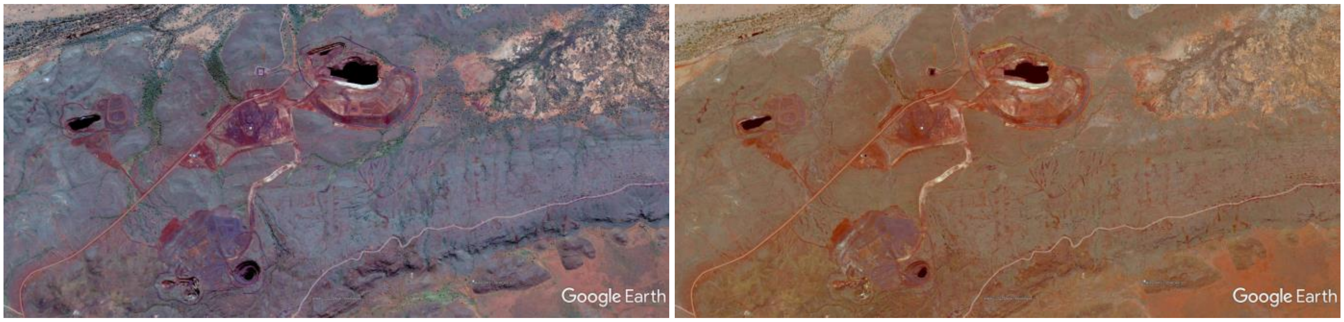
Independent assessment concluded that the wetlands support substantial ecological values, both aquatic and terrestrial, demonstrating the effectiveness of the rehabilitation efforts. These wetlands also have the potential to provide opportunities for environmental education, research and eco-tourism.

Figure 61: Completed rehabilitation at Beenup Mineral Sands Mine

3.12 Pilbara Iron Ore Mine, Western Australia

The focus of this section is reporting on the cost-effective rehabilitation during operations of the Pardoo Iron Ore Mine in the Pilbara region of Western Australia.

Figure 62 shows two Google Earth images over time of the Pardoo Iron Ore Mine, located 75km east of Port Hedland in the Pilbara region of Western Australia.



(a) (b)

Figure 62: Google Earth images of Pardoo Iron Ore Mine going back in time: (a) April 2015, and (b) October 2014

3.12.1 Climatic setting

Pardoo Iron Ore Mine is located in an arid, sub-tropical climatic region, with a summer-dominated mean annual rainfall of 316mm, falling predominantly during the 4 months from December to March, and the average number of days of rain/year is 21 days, or only 6% of the year (www.bom.gov.au). The minimum and maximum recorded annual rainfall totals are 18mm and 1,075mm respectively, with up to 630mm recorded in a single month (March). The site climate is strongly net evaporative on average.

3.12.2 Rehabilitation of Pardoo Iron Ore Mine

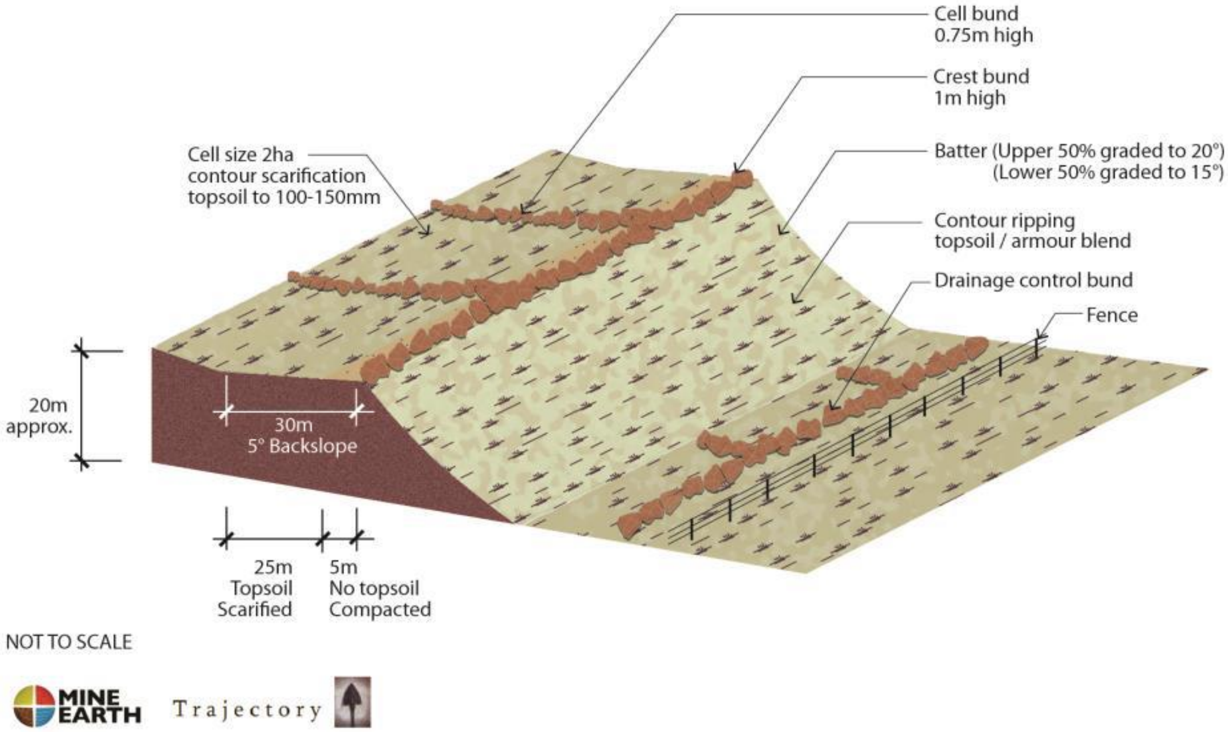
McKenzie et al. (2013) described mining and integrated closure planning of the Pardoo Iron Ore Mine from October 2008 to a then projected completion of mining during 2014. Closure planning commenced during the feasibility stage of the project in 2008, with detailed closure planning from 2010, including targeted investigations to resolve gaps and risks, and to enable the development of a detailed mine closure plan. The aim was to integrate closure planning outcomes into the operational phase of the project to realise financial and operational efficiencies.

The project comprised six iron ore deposits mined via 11 open pits at a rate of approximately 3Mtpa. Closure works commenced during 2013 and were to be finalised in 2014. Post-closure monitoring was to continue for 10 years, followed by an application for relinquishment.

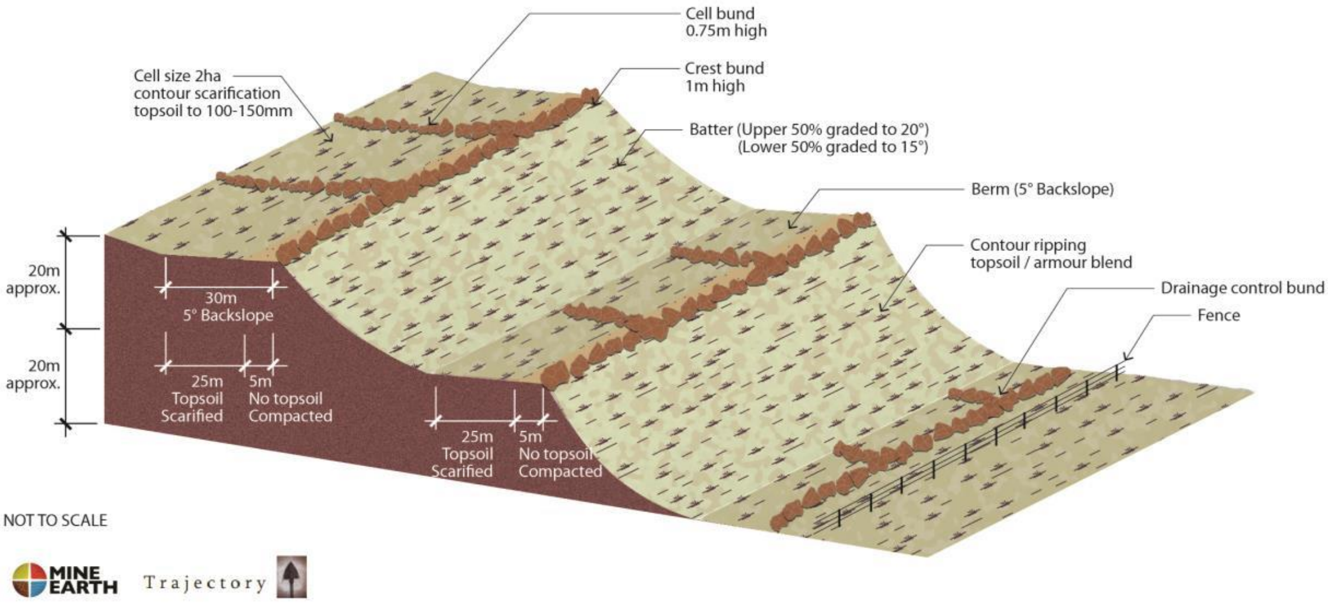
The waste rock was largely blocky and competent. Single and double batter landform waste rock dump design (Figure 63) was proposed, incorporating following key design principles:

- Minimise the potential for water flow onto landform batters.
- Encourage surface water infiltration on landform surfaces.

- Reprofile the landform batters to a concave shape, comparable to an eroded slope after 250 years of modelled erosion.
- Constrain slope lengths to less than 100m.
- Limit vertical batter heights to 20m, beyond which a mid-slope berm is recommended.
- Berms should accommodate peak maximum flows and should be level.
- Final batter surfaces should consist of suitably coarse and durable rock, with rock armoring placed where required.
- Landform surfaces will be sheeted with topsoil where available or subsoil.
- Landform surfaces will be cross-ripped on the contour.
- Spread area specific seed mix (native grass, shrub and tree species).
- Sediment control measures will be implemented around the perimeter of each waste rock landform.
- Fencing will be installed where practicable to minimise grazing during vegetation establishment



(a)



(b)

Figure 63: Landform waste rock dump design: (a) single batter, and (b) double batter

4 Conclusions and recommendations

4.1 Factors contributing to stable mined landform design

The factors contributing to stable mined landform design involve physical, chemical and biological interactions, which vary with the mine's climatic, topographic and seismic settings (Williams, 2021), the nature of the commodity mined, the mining and processing methods employed, and the resulting mine wastes and their storage. In addition, account must be taken of the affected communities, socio-economic and geopolitical issues, and opportunities to add value post-mining (Williams, 2019 and 2021) to replace the value lost through the cessation of mining and any legacies mining leaves.

In the Australian context, the dominant mine site setting is climate, with Australia's topography generally flat to gently undulating, and the seismicity low. Australia's low topographic relief results in relatively low height surface waste rock dumps and tailings storage facilities because of the high cost of extending them higher and aesthetic constraints imposed on waste storage heights by the surrounding terrain. In turn, surface waste storages in Australia tend to occupy large footprint areas.

Australia's low seismicity has meant that earthquake loadings during the operational phase are generally insufficient to threaten the seismic stability of open pit slopes, surface waste rock dump slopes, or the slopes and stored tailings within surface tailings storage facilities. However, because closed mine sites must remain safe, stable, and non-polluting in perpetuity, post-closure earthquake loading can be sufficient to threaten the seismic stability of the slopes and stored tailings within surface tailings storage facilities, in particular. Hence, tailings storage facilities should be made stable landforms post-closure, with negligible risk of credible failure modes.

The 12 case studies identified and described in this Project Report cover a range of Australian climatic settings. The climatic settings considered range from sub-tropical North Queensland and the Northern Teritory with a hot and humid wet season (Kidston Genex and New Century, and McArthur River mine sites); through sub-tropical South-East Queensland and New South Wales (New Acland and Bengalla mine sites); the Mediterranean Latrobe Valley and Sovereign Hill mine sites in Victoria, at Kanmantoo Copper Mine in South Australia, and at Collie Coal Mine and Beenup Mineral Sands Mine in South-West Western Australia; the temperate, wet maritime climate of Henty Gold Mine on the West Coast of Tasmania; and the arid, sub-tropical climate of Pardoo Iron Ore Mine in the Pilbara, Western Australia.

The key climatic issue in the Australian context is extreme rainfall events, particularly those following periods of drought that restrict revegetation, resulting in excessive erosion. Erosion is exacerbated by the conventional flattening and topsoiling of mine waste slopes, which increases rainfall runoff and greatly increases erodibility. Possibly during the operational phase, and certainly post-closure, open pit slopes, surface waste rock dumps, and surface tailings storage facilities must be designed to accommodate the Probable Maximum Flood (the largest flood that could conceivably be expected to occur once in 10,000 to 10,000,000 years). The impact of climate change on the severity and frequency of flooding events must also be taken into account.

In the Australian context, the annual rainfall typically ranges from about half to in excess of twice the annual mean rainfall. Extreme rainfall events can impact any part of Australia, although they are most problematic in the wet tropics and sub-tropics as a result of cyclonic rainfall depressions. On the West Coast of Tasmania, rainfall is more steady throughout the year, and shows less variability from year to year than in northern Australia.

The range of mineral commodities considered in the Project included bulk commodities such as coal (New Acland, Bengalla, Loy Yang and Collie) and iron ore (Pardoo), precious (Kidston, Sovereign Hill and Henty) and base metals (New Century, McArthur River and Kanmantoo), and metals processed from oxide ores (Beenup). Most of the mine site case studies considered were open pit operations, with open pits, overburden and waste rock dumps, and tailings storage facilities. Initially McArthur River Mine, plus Sovereign Hill and Henty Gold Mine involved underground mining, with Henty using cemented tailings paste backfill of their underground operations.

4.2 Stable mined landform design and regional benefits post-closure

There are numerous examples of legacies left by unacceptable mine closure and transition to regional benefit. This Project identified and described a number of rehabilitated mine sites that contribute lasting regional benefit. The Kidston Genex Renewable Energy Hub is the exemplar Australian example of contributing regional benefit post-closure, and is world-leading. The construction by Genex of the Solar Farm on the tailings storage facility, and the current construction by Genex of the Pumped Storage Hydro Project involving the two pits, provide a long-term repurposing of the mine site. The construction activity is providing employment and the operation of Renewable Energy Hub will provide ongoing employment and occupation of the site. Ongong maintenance of the site will be possible through its repurposing. It will also enable the seepage of poor quality to be collected where it emerges at low points around the surface waste rock and surface tailings storage facility, and pumped back to the open pits. Kanmantoo Copper Mine has undertaken the rehabilitation of the combined surface tailings storage facility and waste rock dump, and proposes a pumped storage hydro use of the pit in collaboration with AGL.

New Century Resources is reprocessing of the stored tailings for zinc recovery, and disposing of the residual tailings in-pit to be below the final pit water level, with all tailings removed from the tailings storage facility so that it will not require rehabilitation. McArthur River Mine has undertaken reshaping, covering and changed operation of the North Overburden Emplacement Facility to mitigate spontaneous combustion and the generation of noxious SO_2, CO and CO_2, and sulfate-contaminated seepage from the facility, to restore the mine's social, environmental and financial licenses to operate. In the future, the mine proposes reprocessing of the stored tailings and disposing of the residual tailings in-pit to be below the final pit water level.

New Acland Coal Mine has undertaken leading practice rehabilitation of its surface and in-pit tailings storage facilities and the progressive backfilling with spoil of the mined sections of the open pit. The rehabilitation of the site has allowed grazing to return, providing yields equal to or better than those achieved prior to mining. Bengalla Coal Mine is rehabilitating the above-ground spoil piles to provide the required visual buffer to the town of Muswellbrook that faces it, and to potentially achieve a post-mining grazing land use. Loy Yang Mine is undertaking the progressive rehabilitation of the surface overburden dump and upper slopes of the open cut as mining progresses.

Pilbara Iron Ore Mine has cost-effectively rehabilitated the mine site during operations in the Pilbara region of Western Australia. Sovereign Hill successfully repurposed the abandoned old gold mine workings for tourism. Henty Gold Mine successfully applied a combined peat and water cover on sulfidic tailings to limit their oxidation and the generation of acid and metalliferous drainage on the wet West Coast of Tasmania. Collie Coal Mine has successfully created a pit lake in an open cut for recreational and/or fishery use, and plans to extend this successful repurposing to other pits, possibly including pumped storage hydro use. Beenup Mineral Sands Mine successfully rehabilitated the mine through the creation of pit lakes.

The 12 mine site case studies described in this Project Report show effective mined landform design, construction and sustainability involving a range of Australian site settings and for a range of mineral commodities, facilitating regional benefits, as summarised in Table 3.

Table 3: Summary of regional benefits post-closure among mine site case studies considered

SITE	REGIONAL BENEFITS POST-CLOSURE
Kidston Genex, North Queensland	Repurposing by Genex of the closed Kidston Mine to a renewable energy/battery hub will ensure a long-term sustainable reuse of the mine site and will allow ongoing management of the environmental impacts at the site
New Century, North Queensland	Reprocessing of tailings for zinc and the final in-pit disposal below water of the residual tailings to eliminate the tailings storage facility environmental liability
New Acland Coal Mine, South-East Queensland	Rehabilitation of surface and in-pit tailings storage facilities, and backfilling of pits with spoil, for a successful return to grazing
McArthur River Zinc Mine, Northern Territory	Rehabilitation of the North Overburden Emplacement Facility to restore the mine's social, environmental and financial licenses to operate, plus the proposed reprocessing of the stored tailings and final in-pit disposal of the residual tailings below water
Bengalla Coal Mine, Hunter Valley, New South Wales	Rehabilitation of spoil piles to create a visual bund from Muswellbrook, and to potentially achieve a post-mining grazing land use
Loy Yang Mine, Latrobe Valley, Victoria	Progressive rehabilitation of Loy Yang overburden dump and the upper slopes of the open cut as mining progresses
Sovereign Hill, Victoria	Successfully repurposing of abandoned old gold workings for tourism
Henty Gold Mine, West Coast of Tasmania	Combined peat and water cover over sulfidic tailings to mitigate oxidation and acidic seepage
Kanmantoo Copper Mine, South Australia	Integrated waste landform design and construction, involving the combining of the old waste rock dump and current tailings storage facility, and proposed pumped storage hydro use of the pit
Collie Coal Mine, South-West Western Australia	Successful establishment of Lake Kepwari in a completed open cut for recreational and fishery use, and relinquishment, with plans to extend this to other pits, possibly including pumped storage hydro use
Beenup Mineral Sands Mine, South-West Western Australia	Wetland rehabilitation and relinquishment of pits
Pardoo Iron Ore Mine, Pilbara, Western Australia	Cost-effective mine site rehabilitation during operations

4.3 Conclusions

This project assessed the geotechnical, erosional and geochemical stability, and acceptability for closure and post-closure land use and/or ecological function, of past and current mined landforms, to inform suitable future final mined landforms for a range of 12 Australian mine site settings and mineral commodities. Key among the mine site settings is the climate and, in particular, the rainfall of the site. The Australian climate ranges from the wet tropics in the north, through the sub-tropics to the Mediterranean in the south, and the temperate, wet maritime climate of the West Coast of Tasmania. The range of mineral commodities considered included bulk commodities such as coal and iron ore, precious and base metals, and metals processed from oxide ores, and the associated open pits, overburden and waste rock dumps, underground workings, and tailings storage facilities.

This project involved a literature search, and input from the experiences of the project's research and industry end user teams on the performance of past and current mined landforms, covering the selected range of 12 Australian mine site settings and mineral commodities. The mine site case studies considered showed effective mined landform design, construction and sustainability in the Australian context, for regional benefit.

4.4 Recommendations for further research

The minerals industry has a reputation for often poor mine site rehabilitation and regional benefits, despite the benefits produced during mining operations. Too few examples of effective, and cost-effective, mined landform design and regional benefits post-closure are publicised. Also, lessons learned are typically not presented. The project has relied largely on published information and unpublished information and data on mined landforms, covering a range of site settings and mineral commodities, from members of the project's research and industry end user teams.

The project presented case studies of effective mined landform design, mine site rehabilitation and transition to regional benefits during operations and post-closure. Further research should be directed at identifying, highlighting and publishing other case studies from the industry of successful mine site rehabilitation, reuse, and repurposing for regional benefit, and directed also at presenting also the lessons learned. The minerals industry is encouraged to make data and examples pubicly available to serve as benchmarks to which future mine site rehabilitation, reuse, and repurposing can aspire. The industry and regions would benefit from a more whole-of-life approach to mining and mineral processing, involving planning, design, construction and operation with effective and sustainable closure front of mind.

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