

The current state of geomorphic landform design in Australia

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Abstract

The Australian mining industry has been constructing geomorphic landforms using geomorphic principles for the last 14 years. The authors have been involved in the design and construction of most of these, totalling over 20 sites across Australia, typically comprising multiple landforms, and primarily (but not exclusively) in the coal mining industry.

Our involvement in the full landform cycle of geomorphic landforms, from initial concepts through to erosion monitoring, has given us the opportunity to review learnings and general concepts in Australia and elsewhere which we have captured in this paper.

We review the current state of geomorphic landform work and briefly discuss three Australian case studies in terms of the design process, the core tenets of geomorphic design in Australia. We also discuss examples of the natural analogues considered relevant for mining landforms in particular soils and climates, and the contribution stakeholders and state regulators have made in facilitating acceptance of more natural landforms in the Australian context, especially in New South Wales.

Integration of soil erodibility testing, aspects of landscape evolution models (LEMs), and erodibility design envelopes has allowed landforms steeper than natural analogues to be constructed and addressed a key concern with the use of natural analogues, namely that site soils are often more erodible and vulnerable than those on natural analogues, with additional risks during the revegetation process. We briefly indicate our approach to the use of rock armouring on these landforms if and where required.

Progress in the last few years has focused on monitoring using high-density LiDAR, and software development and improvement. Fundamentally, monitoring allows for progressive improvement and confidence in the design outcomes, which can then be reflected in software improvements. We have moved away from the use of traditional software using break lines to the use of Python scripting working on gridded surfaces, both for efficiency and to obtain outcomes that better align visually with our local landforms. The functionality of this tool is discussed to help others adopt a similar if applicable.

Keywords: *geomorphic, landforms, Australia, review*

1 Introduction

As part of the environmental and social contract inherent in extractive industries there is an expectation that the disturbed land will be returned to an acceptable state (Williams 2023). While many types of landscapes result from mining, the focus here is on overburden dumps, both in-pit and out of pit.

Developing a sound approach to designing such waste landforms needs to consider the long-term stability against climatic erosive forces (Hancock et al. 2003). The intent is that the landform will eventually function as a natural landscape and support an ecosystem representative of the area (Hancock 2016). Several different approaches to designing such landforms have been developed.

Most closure requirements require an erosionally stable landform as measured by erosion rate and rill depths. Erosion can impact topsoil and revegetation growth, downstream receptors, and geotechnical

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stability (Williams 2023). Mitigation of water erosion relies on controlling the energy of the flowing water (Sawatsky & Beersing 2014).

Control of the energy of runoff can be achieved by options such as shortening the slope length (Hancock et al. 2003), reducing the slope gradient, reducing the volume of runoff by increasing infiltration, or improving the resistance against erosion through improved vegetation or rock cladding or similar (Witheridge 2023).

Geomorphic landform design has been around as a concept for many decades, but the advent of machine guidance in the early 2000s was a key milestone. The work in New Mexico in 2001 (Bugosh & Epp 2019), Canada (Sawatsky et al. 2008) and Spain (Duque et al. 2021) were the initial proponents of this approach. All were based on replicating stable natural landform processes.

In Australia, a small demonstration landform was constructed at Drayton (Hancock et al. 2019) before a large open cut design Mangoola Open Cut Mine adopted the approach in 2011. Within a few years, it became apparent that the community and NSW Resources Regulator favoured this approach as being more environmentally diverse and more visually integrated with the environment (Kelder et al. 2016; Dressler & Waygood 2022).

The authors have been involved in the design and construction of geomorphic landforms at more than 20 sites, most including numerous landform features, across a range of climatic conditions across Australia. The intent is to present some findings concerning geomorphic landform design in the Australian context.

2 Australian landform settings

Modern mining in Australia has been occurring since approximately 1799, though mining of ochre for pigments has been occurring for at least 60,000 years. Some main mining areas and associated soils and climatic conditions are discussed below:

- The iron ore mines of the Pilbara region: the Pilbara area is some of the oldest exposed landscape in the world. This is a sparsely populated arid area with rainfall around 300 mm/annum that nevertheless experiences cyclonic rainfall events which can erode mine waste significantly. Vegetation is sparse and seasonal, and although designs tend to favour water retention to support vegetation, erosion is typically controlled by the particle grading. The mining method for iron ore is generally truck and shovel, and landforms are typically bench batter designs. Concave and geomorphic designs have also been constructed but are limited in number.
- Coal mining in the Hunter Valley: this area rainfall typically around 700 mm/annum and landforms generally shed water back to the environment. The area is a tourist area, and mining is often near communities which drives a keen social awareness. Soils can be dispersive.
 - Mining has transitioned away from draglines and is generally truck and shovel. This mining method and the social issues have made this an ideal area for geomorphic landforms and there are over 20 sites using this approach, ranging in size from around 100–4,500 ha.
- The coal mining areas of the Bowen Basin and Queensland: rainfall varies across this area from 600–1,000 mm, but it experiences significant cyclonic rainfall events. Soils can be notably poor and dispersive, with vegetation cover exposed to extremes of drought and high rainfall; a highly erosive environment.
 - The mining method is predominantly dragline which limits the flexibility for the final landform design which can result in additional earthworks costs to form non-linear landforms. Geomorphic designs have been completed on at least two sites that we are aware of, potentially more.
- The northern portion of the Northern Territory is a tropical area with an average rainfall of between 1,200 and 1,800 mm in the north and is exposed to monsoon rainfall conditions and cyclonic events.

- Uranium and bauxite mines are located in these northern areas, which have varying degrees of vegetation. Work on geomorphic landforms is being undertaken on some sites with a geomorphic design being planned for the Ranger Uranium Mine (Ranger).

3 Australian regulatory setting

In the Australian context, mine closure criteria mandate that final landforms must be safe, stable, and sustainable for the agreed post-mining land use (NSW Resources Regulator 2021b). A fundamental design requirement is achieving long-term erosional stability.

There is currently no single, nationally mandated acceptable erosion rate for mine rehabilitation in Australia, and the onus is generally on the client to demonstrate acceptable erosion rates. A review of Australian practices shows these approaches include a range of options such as:

- Rates of soil formation/renewal target erosion rates equal to or less than the rate of new soil formation (Hancock et al. 2015).
- Comparison to natural analogues, arguing that erosion rates are aligned to measured erosion rates from the surrounding, stable, and undisturbed landscape (So et al. 2018). There is an argument that newly constructed landforms cannot be expected to match surfaces that are significantly older within a short period of time.
- Risk-based frameworks where the acceptable erosion rate is not a fixed value but is scaled according to the risk posed by the landform, distinguishing between (for example) a relatively benign waste rock dump and a potentially acid-forming one (Howard & Loch 2019).

The accepted values in Australia vary significantly, but most commonly seem to be in the range of 5–10 t/ha/annum, to lower values in specific circumstances (Howard & Loch 2019).

There is a requirement to verify that proposed designs will meet these stability criteria through both erosion modelling and assessments (Hancock et al. 2025) and monitoring of constructed landforms before relinquishment (Commonwealth of Australia 2016).

Beyond this quantitative assessment of physical stability, visual amenity remains a key criterion, requiring the final landform to be compatible with the aesthetic character of the surrounding landscape. The inclusion of micro-relief and drainage lines, that are visually consistent with surrounding topography, is a further obligation which the regulator has required from mine operators (NSW Resources Regulator 2021b).

4 Landforms

4.1 Natural landforms

Landforms that we work with are generally shaped by water erosion, with the erosive forces from rainfall and runoff being resisted by the soil, vegetation and other strata such as bedrock. Landforms are either stable where there is equilibrium between these forces, or still in a state of flux due to recent changes that may have occurred (Willgoose 1994). In a stable landform, the topography is configured to minimise the net energy available for further erosion, that is, the landscape develops drainage networks and hillslopes appropriate to the driving and resisting forces (Sawatsky et al. 2008).

This process of stabilisation is achieved through progressive erosion often over long and even geological time periods until the number of drainage lines is appropriate to the catchment area (drainage density), achieved through formation of new drainage lines, widening or flattening of drains and adjacent slopes, or encountering a more resistant (Hancock et al. 2020). An example of a typical natural landform is shown below in Figure 1. This landform is located just to the north of the Hunter Valley Region of New South Wales (NSW) Australia. The flow lines on this landform are shown in Figure 2.



Figure 1 An example of a natural landform north of the Hunter Valley, New South Wales (Google Earth 2023)

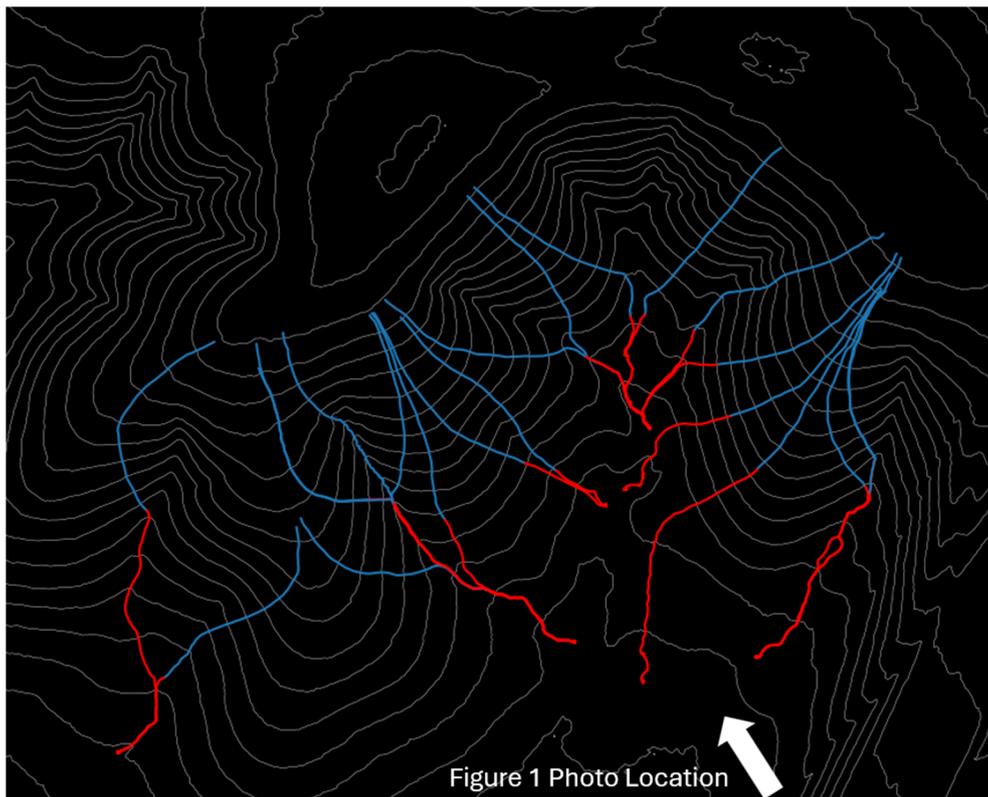


Figure 2 Selected flow paths on the natural landform, the length of the blue portion is 100 m, the red portion is downstream of the blue. The location of the photo in Figure 1 is the bottom of this image

4.2 Mining landforms

The primary goals for any post-mining landform are to ensure it is safe, stable, non-polluting, and suitable for the intended final land use. The design must also be visually compatible with the surrounding landscape and be achievable in a cost-effective manner (Williams 2023; Hancock et al. 2025):

- Traditionally, post-mining landforms involved engineered landforms with uniform slopes and gradients, with contour banks used to limit slope lengths. While simple to design and relatively easy to construct, these structures are not in a state of natural equilibrium and their long-term stability is questionable without a commitment to ongoing, and potentially perpetual, maintenance (Commonwealth of Australia 2016).
- The geomorphic approach endeavours to achieve natural equilibrium by learning from nature to understand what equilibrium looks like in the local climate and soil conditions. Importantly, it is

generally accepted that an appropriate natural analogue should be an alluvial analogue, that is, free of bedrock, stable, and in the local environment. This statement is key to understanding the extent to which the key parameters from a natural analogue can be applied to a mining landform.

A geomorphic design will typically be achieved by using the following core principles (Bugosh & Epp 2019; Duque et al. 2021; Hancock et al. 2020):

- an appropriate drainage density to limit overland flow lengths and catchment areas of drains
- concave drainage lines, becoming flatter as their catchment area increases
- overland flow path lengths limited based on the steepness of the slope
- limited linearity. Instead, diverging flows on ridges and converging flows in valleys.

We also consider that the average slope of the design surface should be appropriate to the analogue, unless other methods of erosion risk are incorporated as discussed in this paper, and that the visual appearance of the design should be consistent with the surrounds.

5 The conceptual design process

Because many geomorphic designs rely on a natural analogue, the inherent assumption is that, because the natural analogue selected is stable, a design that uses the same typical parameters will also be stable. However, mining landforms are generally steeper than alluvial analogues, due to both space constraints, and because a steeper landform requires less dozing to reshape it.

In addition, mining is a dynamic in nature, and the design process needs to be able to accommodate changes in volumes and constraints.

It is therefore key to be able to understand what the limits are for landforms in terms of slopes and height for specific materials on a particular site so that a range of options can be considered.

The basis for this process is to first understand the erosion for a particular material on a linear slope. This can be done by several ways, from rough estimates using the Revised Universal Soils Loss Equation or using a calibrated numerical model for erosion such as the Water Erosion Prediction Project (WEPP) model (Williams 2023).

To apply this to a 3D environment, we typically generate an erosional design envelope as set out below.

5.1 The design envelope

The erosion rate for a given linear slope (where runoff can be assumed to occur uniformly downslope) is proportional to the gradient and slope length. To be able to assess more complex slope geometries where converging or diverging flow may occur it is necessary to combine slope length (or catchment area) and gradient into a single function. This single function embodies a concept of energy available to drive erosion. For a given site it is possible to define a target value for this function which separates slope length and gradient pairs which are stable from those that are not (Figure 3). The target value used is dependent on the local soil, vegetative and climatic conditions and the acceptable erosion rates for the site.

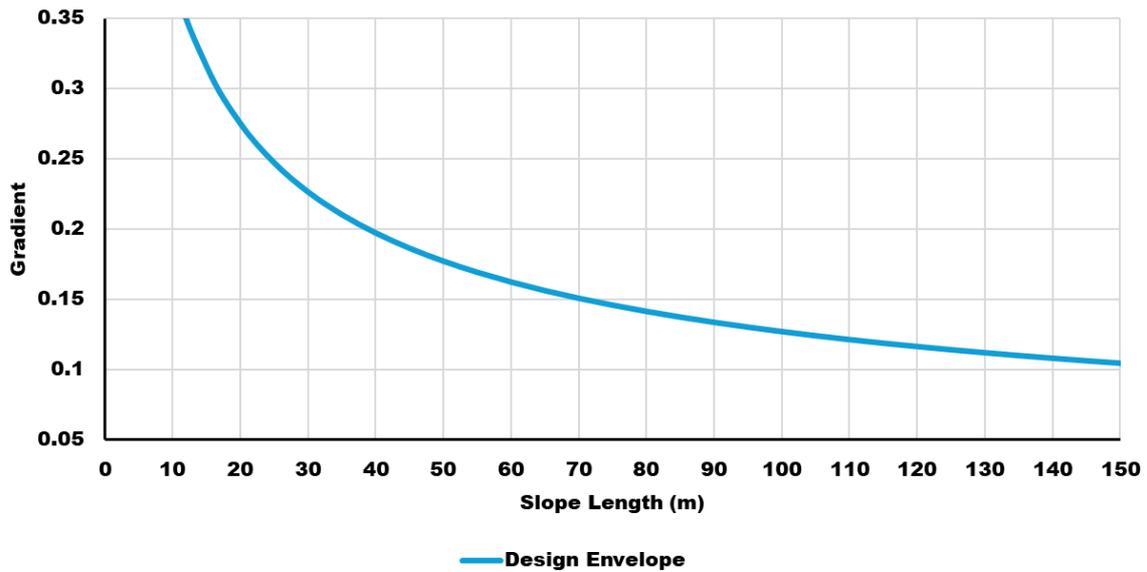


Figure 3 An example of a design envelope for a site. Note that the acceptable range would be below the design envelope

We have approximated this computation by using a simplified version of the Einstein–Brown equation which is also used in the SIBERIA landscape evolution model (LEM) to calculate a sediment discharge due to a particular flow rate at a particular slope (Willgoose et al. 1991). We refer to this as the topographic factor (TF) computed as:

$$TF = Slope^n \times Catchment Area^m \quad (1)$$

where m and n are parameters that need to be calibrated for site specific soil and climatic conditions. While the TF can then be computed on any surface, the limiting value for the design needs to be assessed, generally done as follows.

- Using a WEPP analysis or similar tool to generate a range of erosion rates for different catchments and slopes and then curve fitting to determine the design envelope (this requires an estimate of what would constitute the limiting erosion rate).
- Analysis of nearby natural landforms such that the maximum TF is only exceeded in drainage lines (refer Figure 4).
- Assessments and improvements based on the performance of constructed landforms.
- Where there is an existing LEM for a site (Temme et al. 2017; Hancock et al. 2025), we can use the outputs from that to assess a target TF.

We will generally not design a TF for a fully vegetated surface, but rather somewhere between the values for bare soil and vegetated surface to allow for robustness while vegetation is still being established.

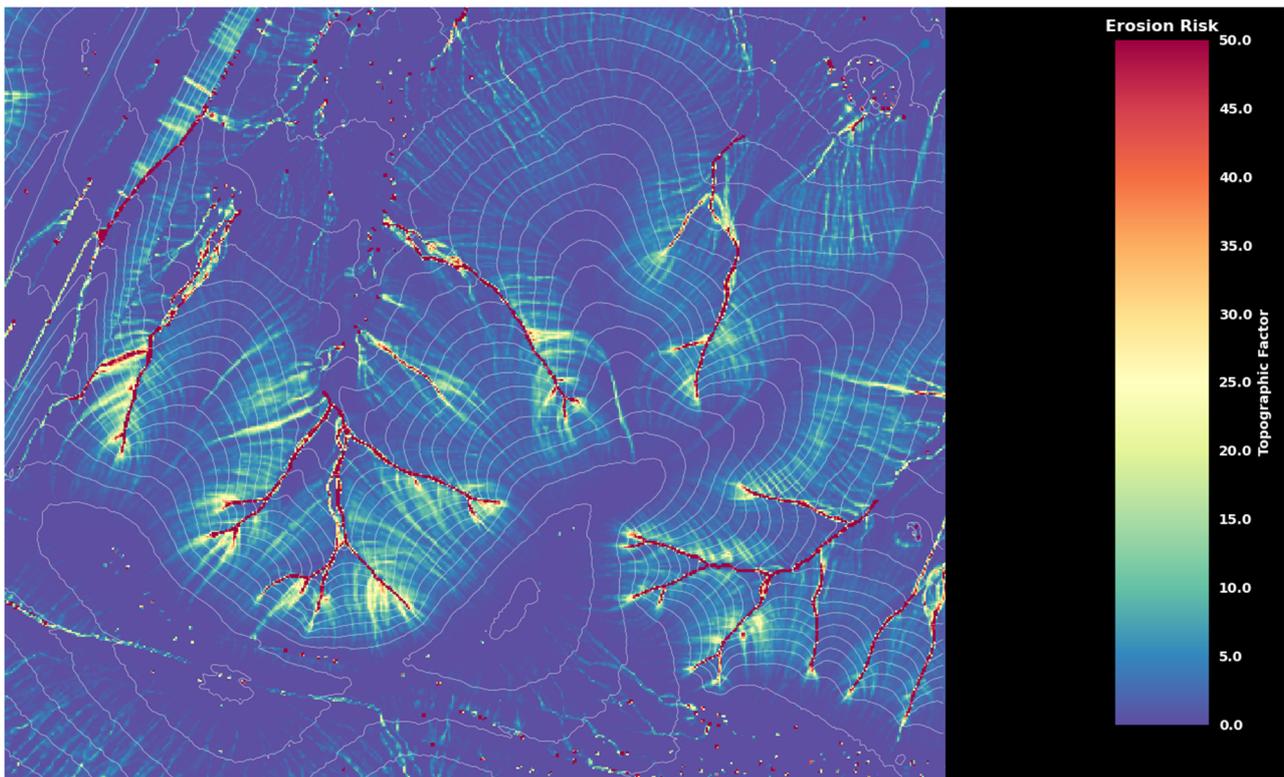


Figure 4 Topographic factor for the natural landform

5.2 The design tools

CAD-based software is traditionally used for landform design, which in turn relies on break lines and triangulations. For very large landforms, we encountered challenges in creating natural-looking landforms and in managing material movement using commercially available software.

We subsequently developed an in-house toolkit using Python scripting on gridded surfaces. While lines are still used to form drainage lines, for the rest, shaping without break lines allows for subtle concave and convex shapes typical of natural landforms.

The value in using a gridded approach, apart from the benefit in shaping, is that:

- Cut/fill calculations are easier when changing elevations on a grid which allows cut/fill balanced shaping to be included.
- Erosion risk assessments are easier on a gridded model as flow tracking to identify areas of flow concentration and slope computations are easier.
- We have found that it is easier to make incremental changes (specifically to pursue a cut/fill balance) to a surface described by points (especially if the elevation of a group of points can be altered) than one described using breaklines only.

5.3 Design validation

The process of design validation to demonstrate landforms are safe and stable varies for different regions in Australia. Generally, validation methods are either suggested or required by the Regulator, and the requirement to be assessed may vary from erosion rate targets to depth of rilling where the integrity of a capping layer is important.

In the Australian context, the use of LEMs has become the standard approach to demonstrate that a design will meet the requirements of the regulatory body. Due to the large number of LEM models which have been undertaken, an extensive knowledge base of local soil and climatic conditions exists.

In NSW the greatest risk of erosion is early in the construction, prior to revegetation, and experience using high-density LiDAR has demonstrated that landforms that erosionally stable in the first few years tend to become progressively more stable, and most erosional issues become apparent early on post-rehabilitation. This provides a good level of confidence in the longer-term performance of these landforms. Conversely, in more arid areas, the short-term performance is not necessarily an indication of longer-term performance, since vegetation is less of a consideration in the overall performance.

6 Construction design

For the geomorphic landforms, we typically provide both the final surface and the temporary benches that will be tipped and dozed down to form the final surface. During construction, we often are required to make adjustments, namely:

1. Refining the surface: the as-tipped benches are often different to the designed benches. Generally, this can be managed within the tolerances of the design surface, but sometimes the design needs to be adjusted. The final details for drainage systems are sometimes completed here, although some sites have found that finalising the drainage earlier minimises the need for smaller equipment later in the construction, provided the surfaces do not change post-design.
2. Optimising earthworks: optimisation of the earthworks is normally undertaken during the design process, but sometimes operational constraints and placement results in additional optimisation required prior to implementation.

6.1 Drainage

The drainage lines are a key part of any geomorphic landform. Most of our sites are ephemeral systems and will only convey flow during storm events, with flows occurring in the valley lines (see Figure 5). The design of these drainage lines is undertaken according to the following considerations (Sawatsky & Beckstead 1996):

- The drainage lines have sinuosity appropriate to their gradient and location in the landform and are generally concave in profile for vegetated surfaces. In practical terms, sinuosity helps limit flow parallel to the drainage line.
- Even for surfaces designed using alluvial analogues, care must be given to the required widths and grades to ensure appropriate tractive stresses and velocities.
- It is worth noting that analogue methods generally assume that rock will not be required, and that some movement of drainage lines through erosion and deposition is both natural and acceptable. In our experience, there are two main challenges with that. Firstly, if the landform is on average steeper than the analogue, one cannot assume stability without the need for rock armouring or similar. Secondly, regulatory requirements generally limit the acceptability of scour and reformation of drainage lines on mined out surfaces.

Consequently, we often incorporate rock into our designs, but with several provisos. The intent is still to form a natural landform without highly engineered features, and to ensure that these features have a lifespan similar to the rest of the landform. Regulators frequently require LEMs to be run for 500 years or longer.

To achieve this, we use an approach referred to as vegetated rock armoured drains. That is, we allow for rock armouring, but design drains so that vegetation is able to stabilise them for all but the most extreme event. Effectively, we need the rock for roughness, but generally velocities will be within a reasonable range for vegetation to be stable. The main benefit of this is that, for normal rainfall conditions, sediment tends to accumulate within the voids in the placed rock, and this process of sedimentation greatly increases the durability of the drain. Further, as part of a natural process, seed will tend to be washed towards the drainage lines, resulting in revegetation of the drainage lines. The following design approach has been developed by observing the behaviour existing drains.

- Two design storms are identified; a smaller storm (which is exceeded more often, the authors generally use the storm with a 10% annual exceedance probability [AEP]) and a larger storm (which exceeded more rarely, the 1% AEP storm event has been found to result in drains with good stability without being overly conservative)

The cross-section and rock layer are designed such that the flow velocity for the more frequent event is less than 1.5 m/s and that individual rocks will not be dislodged during the larger event (the possibility of flow concentrating within a smaller portion of the drain is considered). The limit of 1.5 m/s has been identified as the maximum velocity for vegetated waterways in the absence of rock (Gregory & McCarty 1986). An example of this output is shown in Figure 5.



Figure 5 An example of a rock drain on a geomorphic landform in the Hunter Valley. This drain is approximately five years old

7 Monitoring

The regulatory agencies across Australia require that the stability of the rehabilitation be demonstrated through monitoring of the constructed landforms. The parameters of most importance to landform design will relate to the movement of sediments across the landform. This can be monitored using survey pins, sediment ponds or survey information.

We have developed a methodology to calculate rill volumes by modelling water flow across a gridded model of a surface with a high resolution (20 points/m²). The calculated erosion volume can be used to determine the erosion rate if the age of the rehabilitation is known. This approach is used to determine erosion rates across several sites (predominantly geomorphic designs) indicative average erosion rates for sites of different age ranges are shown below (Table 1) (Dressler & Waygood 2024).

Table 1 Measured erosion rates for six sites across the Hunter Valley rehabilitated with geomorphic landforms

Site age	Average erosion rate (tons/ha/annum) across six measured sites
0–5 years	20
5–10 years	4.34
>10 years	1.5

8 Sites

The progression of geomorphic landform in Australia is shown in Figure 6 and is based on sites that we have been involved with. There are likely a few additional sites that we are not aware of. Effectively, there was an early period of demonstration and development, and then more widespread acceptance and even regulatory prescription in NSW for a geomorphic approach.

The shift towards this method has been, in our view, largely driven by community preference for more natural-looking landscapes with ecological habitat diversity, and regulatory concerns around the need for ongoing maintenance post-closure of traditional designs.

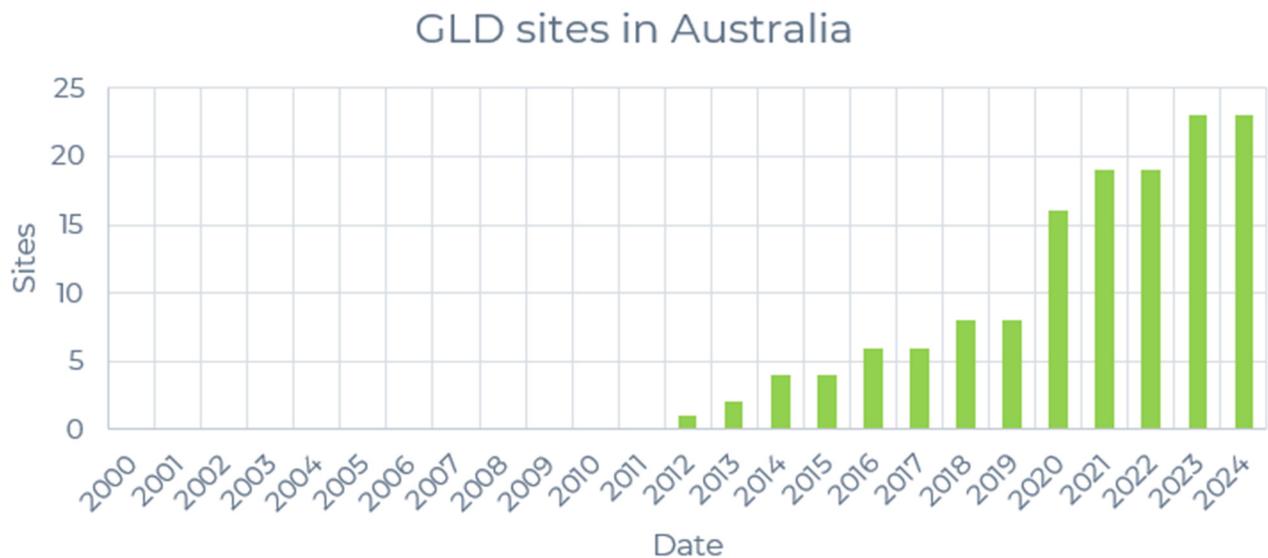


Figure 6 Progression of geomorphic landform designs in Australia

We briefly describe three case studies below, focusing on:

1. The influence of societal expectations in the decision to implement a geomorphic design.
2. The application of geomorphic principles to repair a failing traditional landform in steep terrain.
3. A design process driven primarily by LEM outcomes.

8.1 Mt Pleasant

Mt Pleasant is a coal mine located in the west of the coal mining area of the Hunter Valley owned by MACH Energy Australia. An ongoing concern of the communities in the Hunter Valley has been the visual impact of mining. Mt Pleasant is located across the floodplain from the town of Muswellbrook (population 16,000) as shown in Figure 7. By adopting a geomorphic design approach (incorporating both micro and macro relief), the horizon line of the landscape could be varied and the lower slopes shaped to align with natural landscapes. The final landform is anticipated to be approximately 200 m high with an average outer slope of 1V:5H (refer to Figure 8). During the design process the predicted erosion of the surface was estimated using an LEM. The identified erosion target rate was taken as being that of the surrounding landscape.

The lower 80 m of this landform has been constructed, and erosion rates are being measured both via erosion monitoring approaches using high-density LiDAR (Dressler & Waygood 2024), and through a trial plot administered by the University of Newcastle. The NSW Resources Regulator (2021a) issued a rehabilitation information release which highlighted the favourable outcomes using the approach and also noted the effective construction and design quality assurance through the use of geomorphic landform design software supported by LEMs, effective quality control during construction and ongoing monitoring of the constructed landform.



Figure 7 The Mt Pleasant mine (centre top) across the Hunter River from the town of Muswellbrook



Figure 8 Artists rendering of the final landform at Mt Pleasant (perspective from Muswellbrook, contours in blue)

8.2 Mountain Block

Liddell Colliery is located in the central Hunter Valley. Coal extraction has ceased and closure operations are underway. The landforms currently under construction are using geomorphic landform design principles. To the north of Liddell is a smaller pit called Mountain Block, the site was excavated into the side of a hill and has resulted in steep slopes. Previous landforms here have attempted to use contour drains to stabilise the landform. These had failed and a geomorphic design was employed to repair the landform (refer to Figure 9). The slopes here are up to 1V:2.5H which proved to be difficult to construct safely.

During the design process, a combination of LEMs and the design envelope approach was used to ensure the landform performed according to the design criteria. The target erosion rates were taken as being equivalent to those of the similar landforms in the surrounding area.

The landform is performing well with erosion rates measured between 2 tons/ha/annum and 9 tons/ha/annum at two years after rehabilitation. Notable is the establishment of vegetation in the drainage lines which has improved the stability of the placed rock.



(a)



(b)

Figure 9 (a) Image of Mountain Block (Google Earth 2018); (b) Recent (2024) image of Mountain Block

8.3 Ranger

Ranger is in the Northern Territory within the boundary of the Kakadu National Park. The area is exposed to high intensity cyclonic rainfall events. The need to design a landform that would erode at an acceptable rate while being acceptable to the traditional owners of the land necessitated a detailed approach. The landform was designed in an iterative manner using successive rounds of landform evolution modelling, field trials and design updates to form a landform option which would behave in a satisfactory manner (Lowry et al. 2020). The target erosion rates here were determined from measured rates of the surrounding natural landforms. An additional parameter of importance at Ranger is the maximum depth of eroded features due to the presence of uranium bearing waste within the landform.

The use of an LEM as a design tool here instead of purely an assessment of a completed design resulted in a design which shares many similarities with a geomorphic landform (refer Figure 10). Shared features include prominent ridge lines and concave drainage lines. This demonstrated a situation where using an LEM in the design process resulted in a design which could have been designed using geomorphic principles only. The time needed to iteratively run LEMs is one of the motivations for developing the design envelope approach to allow faster design iteration.

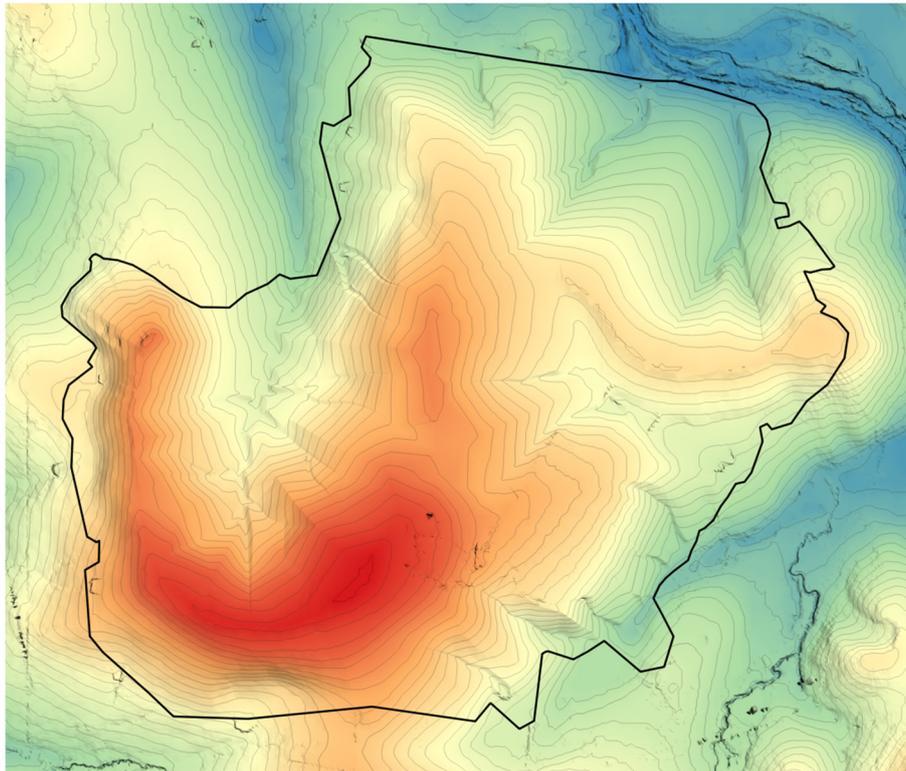


Figure 10 Ranger final landform design (within black polygon)

9 Conclusion

The application of geomorphic landform design in the Australian mining industry has evolved from a novel concept to a widely accepted and often preferred practice for mine closure, particularly in NSW, but increasingly elsewhere.

The Australian approach has progressed beyond dependence on stable alluvial natural landforms to address the common challenges of steeper slopes, exposure during rehabilitation, and the challenges of more erodible soils found on mine sites. Importantly, this has required learnings on over 20 sites to balance regulatory requirements, operational constraints, and stakeholder expectations. While the approach is relatively mature in some areas, inevitably there will be ongoing learnings and improvements. Key for us has been the development of new tools and approaches, including the use of Python-based design tools with grided surfaces, and then closing the knowledge loop in terms of soil and vegetated surface erodibility, starting off with a “design envelope”, applying it in 3D using the TF, validating it with LEMs on some sites, and then undertaking detailed erosion quantification on the as-built surfaces to track performance. This then feeds back into the design process. The results have been encouraging over a period of more than a decade now, both from an erosional perspective, and the better visual and ecological outcomes.

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