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The role of erosion models to benchmark stable post-mining landform designs

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Abstract

Robust landform design increases the likelihood of establishing a stable landform. Final landform design requires clear, well-defined objectives aimed at ensuring erosional stability, particularly by reducing rill formation and eliminating gully erosion.

Erosion modelling provides a powerful way to test and compare landform design options. This requires a competent understanding of the underlying hydrological and sediment transport processes used by the specific model. This knowledge must then be combined with an understanding of soil physical functions and erosional processes along with site-specific information regarding material properties, climate setting, the receiving environment and post-mining land use.

Model selection is a critical element, and the required complexity and accuracy of the modelling study are related to site risks. The model must be suited to the task required of it and supported by laboratory and field data. Site-specific parameters should be developed and are preferred over generic parameters. The model selected must have been tested and validated in a relevant context.

In developing leading practice advice on erosion modelling, we identified that appropriate target erosion rates are crucial for modelling purposes. Gully erosion is a critical failure point for landform stability; exposure of underlying contaminants is not acceptable, and rills are the precursor to gullies. These principles inform the target rate for the modelling study. Target erosion rates are useful for modelling purposes, but any erosion rate is unacceptable if it leads to exposure of hostile materials and impacts to receiving environments in the final landscape.

Designing a landform to avoid rill development will establish the benchmark for a stable landform. Provided the landform is constructed as per the design and achieves other interrelated objectives such as necessary rates of vegetation establishment, armouring of the surface and/or appropriate water management strategies, there will be greater confidence that design objectives can be achieved and sustained post rehabilitation.

Keywords: *final landform design, target rates of erosion, rills, gullies, stable landform*

1 Introduction

For post-mining landforms to be stable and functional they require careful design informed by an understanding of material properties, climate setting, the receiving environment and post-mining land use (PMLU). Arbitrary designs developed without due consideration of site-specific circumstances and materials do not represent leading practice.

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A variety of tools are available to inform the landform design. These include laboratory and field-based investigations to understand material properties (salinity, potential for development of acid and metalliferous drainage (AMD), pH, permeability, water storage capacity, chemical fertility, erodibility and physical stability), predictive erosion models (e.g. RUSLE and WEPP) and landform evolution models (LEMs) (e.g. SIBERIA, CAESAR, CAESAR-Lisflood). Surface survey techniques such as digital photogrammetry on bare surfaces or high-resolution lidar can be used to develop digital elevation models (DEMs). They provide a topographical understanding of the surrounding landscape, at a variety of scales and at different points in time.

Predictive erosion modelling provides a powerful technique to test and compare landform design options (Hancock et al. 2008). Modelling can be used to see how varying height, slope length, the use of different materials and surface protections will influence stability and ultimately help to gain insights and arrive at an optimal landform design. Outputs from modelling studies can identify critical landform geometry thresholds and minimum groundcover levels necessary to ensure long-term erosional stability (Loch et al. 2025). Modelling studies also provide insights into the likelihood and spatial distribution of rill and gully formation, soil loss rates and the long-term evolution of the landform surface (Hancock et al. 2025).

The design process should be iterative, initiated early in the mining process and regularly revised in response to changes in understanding or knowledge of key aspects (Mackenzie & Smedley 2024) and access to more data. Landform design requires planning and a coordinated strategy but provides several benefits such as:

- reduced material movement and the resultant cost savings
- optimised final landforms in regard to shape, rates of erosion, vegetation establishment and ecological integration
- increased potential for sustainable use and minimal ongoing management of the landform post closure (Hancock et al. 2024, Loch et al. 2025).

The Office of the Queensland Mine Rehabilitation Commissioner has published 2 technical papers on designing final landforms using erosion and LEMs – Hancock et al. (2025) and Loch et al. (2025). Building on the advice presented in those publications, this paper explores how robust predictive erosion modelling studies can be used to establish benchmarks for stable post-mining landforms by optimising designs that prevent rill initiation.

2 Threshold erosion point

In Queensland, many productive and environmentally sensitive areas are located adjacent to mining operations. For example, Bowen Basin mines are located in catchments that drain to the Great Barrier Reef (GBR) Lagoon (Australian Bureau of Statistics 2010) and suspended fine sediment is considered a pollutant. The predominant source of sediment to the GBR Lagoon has been determined as a combination of gully and streambank erosion and subsoil erosion from hillslope rilling (Kroon et al. 2013).

Post-mine landforms such as waste rock dumps and tailings storage facilities are prone to erosion (Department of Mines, Industry Regulation and Safety 2021). In Queensland, the importance of a physically stable post-mining landform is recognised by requirements that rehabilitation achieves safe, stable, non-polluting conditions that sustain a PMLU (*Environmental Protection Act, 1994* [Government of Queensland 1994]). The significance of erosion can be demonstrated using a hypothetical scenario.

Consider a simple, linear hillslope, 25 m high, 100 m wide, with a slope gradient of 25% (1V:4H), so that the horizontal batter length is 100 m (Figure 1). The landform is constructed from a material that has a bulk density of 1.4 t/m^3. Sheet erosion on the landform occurs gradually and cumulatively over time as it involves the removal of thin layers of soil across a large area and is reported as a soil loss rate of t/ha/yr. Rill and gully erosion tends to be event driven and whether a rill or gully is formed by a single event or across a period (e.g. one year) is dependent on the rainfall intensity and duration of specific events and the soil's susceptibility to erosion. For simplicity, it is assumed that rill and small gully lengths are 100 m (large gully length 50 m) and dimensions given are the average width and depth along the length of actively eroded slope.

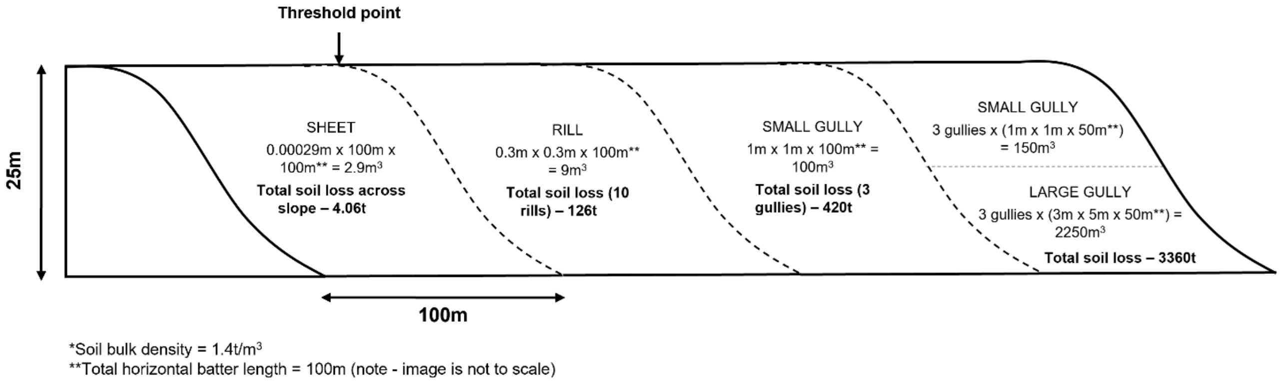

Figure 1 The impact of different types of erosion on a hypothetical hillslope

Sheet erosion, at an assumed rate of 4 t/ha/yr, will denude the landform by 0.29 mm/yr. This does not appear to be significant. After 25 years at this erosion rate, only 7.2 mm of material will have been lost from the landform surface. However, there is a high-risk period when newly constructed landforms initially experience higher rates of erosion, until groundcover is present and/or surface armouring has developed at rates sufficient to protect the surface from raindrop impacts and overland flows (Department of Climate Change, Energy, the Environment and Water 2002). Sheet erosion typically occurs during this high-risk period, and at rates greater than soil renewal, will result in the loss of topsoil and organic matter (Queensland Government 2013; Department of Natural Resources and Environment Tasmania 2014). This inhibits vegetation establishment, starting a cycle of failed vegetation and erosional instability.

Considering the hypothetical hillslope, Figure 1 illustrates increasing soil loss rates as the landform develops rill erosional features that transform into small, and then large gullies over time. When the landform is affected only by sheet erosion at a depth of 0.29 mm, the volume of soil lost from the hillslope is approximately 2.9 m^3. If a single rill 30 cm deep and wide develops down the hillslope, the volume of soil lost from this rill is 9 m^3 (equivalent to 12.6 t). However, rill frequency across a slope is often in the order of a rill every 5–10 m (pers. comm, Rob Loch, 31 March 2026) (Figure 2). Assuming a rill every 10 m, the volume of soil lost from the hillslope, solely attributed to rills, increases to 90 m^3 (126 t). As rills can develop quickly under intense storms, this erosion amount may be close to an annual average. This would logically be in addition to the soil loss occurring over the remaining unaffected area from sheet erosion. If erosion rates are high and the landform construction creates flow concentrations, the rills could rapidly coalesce into small gullies (1 × 1 × 100 m) with a cross-slope spacing of 30 m (Figure 3), and the volume of soil lost then increases to 300 m^3 (420 t). Finally, on the bottom half of the slope, the small gullies can develop downslope into large gullies (3 × 5 × 50 m). The cumulative soil loss from small gullies on the top of the batter and large gullies on the bottom now results in soil loss reaching a volume of 2,400 m^3, which is equivalent to 3,360 t. In that instance, over 99% of the erosion that occurs on this landform is due to detachment of soil particles and their transfer via gullies. Such extreme patterns of erosion are not uncommon, unfortunately. The time taken for such features to develop is highly dependent on rainfall and can vary significantly, but in this case the volume of soil lost when gullies develop is typically such that the rehabilitation effectively fails.

This example illustrates how erosion can dramatically increase if rills and gullies form. Where rills are not removed (for example, by cultivation), they continue to concentrate water and typically develop into gullies (White 2006). Rill initiation is considered a threshold point at which a series of cascading events occur, such as:

- an increasing order of magnitude in soil loss rates
- increasing numbers of erosion features (i.e. multiple rills and gullies)

- increasing rate of hillslope instability
- increasing cost to repair or remediate erosion features
- escalating potential for the incised erosion to expose underlying materials that may themselves be highly erodible or create offsite concerns
- increasing risk that the PMLU will not be achieved.

Further discussion regarding the processes of concern, that is rill and gully development, and its importance when determining failure mechanisms for mine landforms, is presented in Loch et al. (2025).

Figure 2 Rill development at consistent spacing across a landform batter on a waste dump in the WA Goldfields Region, 17 November 2004

Figure 3 Gully development at consistent spacing across a landform batter on a waste dump in the WA Goldfields Region, circa 2005

3 Establishing the benchmark for a stable landform

An optimal landform design, modelled to avoid rill development, establishes the benchmark for a stable landform. A landform's intended function, and the likelihood and consequence of landform failure should inform the design process.

3.1 Target erosion rates for modelling studies

Target erosion rates can be used in a modelling study to guide whether a modelled outcome achieves the required objectives for a landform. However, when undertaking modelling studies to design a post-mine landform it is challenging to select a target erosion rate as there are no universally accepted erosion modelling targets applicable to mine rehabilitation. It is noted that the target erosion rate used in a modelling study is not the same as a threshold value articulated in a completion criterion and this is discussed in more detail later.

The principles related to the concept of 'acceptable rates of erosion' are considered in greater detail by Howard and Loch (2019). Key principles that informed the approaches outlined in Hancock et al. (2025) and Loch et al. (2025) are:

- Gully erosion is a critical failure point for landform stability.
- Exposure of underlying contaminants is not acceptable.
- Rills are the pre-cursor to gullies.

As presented in Figure 1, rill initiation is considered a threshold point and consequently, prevention of rill initiation should become an objective for the landform design. An optimised landform design mitigates erosional triggers, such as long slope lengths, that drive the development of rills. By modelling with a target erosion threshold, predictive erosion models can be used to demonstrate achievement of this objective (Hancock et al. 2025). Careful selection of a target erosion rate that conservatively reflects a rate of erosion which prevents development of rills and gullies will ensure the critical threshold point is incorporated into the design process (Loch et al. 2025).

Supported by the conclusions of published studies and monitoring data of mine rehabilitation, a long-term average erosion rate of 4 t/ha/yr for a landform slope is proposed as a conservative modelling target (Loch et al. 2025). However, it is recommended that a weighting be given to this rate based on site-specific risk. Noting the objective that modelling studies inform a design which will be used to benchmark a stable landform, applying a weighting recognises the need for increased conservatism when modelling a high-risk site and provides flexibility in modelling low-risk landforms. For example, a low-risk landform such as one constructed from materials of low erodibility, containing no encapsulated waste or with low connectivity to fluvial systems, could reasonably have a target average erosion rate increased by 100% to 8 t/ha/yr. Conversely, high-risk landforms such as those constructed from erodible materials, containing encapsulated waste or with high connectivity to fluvial systems, should have more stringent target rates applied as a modelling target (e.g. 50–75% reduction to 1–2 t/ha/yr).[†]

Often, a study that only considers average rates of soil loss across a slope will not be sufficient to optimise the final landform design, for example where a landform is encapsulating hostile materials or preventing generation of contaminants. In these circumstances, a target erosion rate for peak erosion, indicating predicted depths of features, will be necessary to ensure the landform functions as required (Hancock et al. 2025; Loch et al. 2025).

3.2 Underlying requirements and assumptions

Models will predict how a design or as-constructed design will perform over time, but the design assessment process must be robust (NSW Resources Regulator 2021).

For any modelling study, it is critical that the model selected is suitable for the task, is supported by laboratory and field data, that site-specific parameters are developed and preferred over generic parameters, and that the model is tested and validated in its context (Hancock et al. 2025; Loch et al. 2025; State of Queensland 2018). Material characteristics, including erosion potential, should be well understood for each material used to construct the final landform.

Evans (2000) presented various methods used to apply erosion models to the task of mine rehabilitation design at Rum Jungle and identified the need for a ‘technology transfer from the researchers to the practitioners, including regulators, mining and environmental engineers and consultants’.

Application of erosion models requires a competent understanding of the underlying hydrological and sediment transport processes used by the specific model. Each model has different functionality and limitations, and these must be considered to ensure the most appropriate model(s) is selected for a landform design study. For example, how well a model can consider different erosional processes is an important consideration (Loch et al. 2025) as are underlying aspects such as the DEM grid size used in LEM studies (Hancock et al. 2025). This knowledge must then be combined with an understanding of soil physical functions and erosional processes along with site-specific information regarding material properties, climate setting, the receiving environment and PMLU. Studies will be undertaken at different stages of mine life and require increasing focus on design performance as closure planning advances. Poorly selected model parameters will likely impact on simulation accuracy and cost to construct a landform and its subsequent performance post construction. Varying an input for an LEM study may not appear to have a meaningful impact on average across a landform but could result in a change of location or intensity of an erosional feature, impacting on the predicted stability of the landform design (Willgoose 2018). There are risks associated with using estimated erodibility parameters in models and this may require the modeller to apply

[†] Site risk classification and description of the level of risk assigned is described in Loch et al. (2025)

a more conservative target erosion modelling rate to adequately accommodate erroneous model predictions (Loch et al. 2025). Such technical competencies take time and application to develop.

Information and practical guidance to assist regulators and less-experienced environmental practitioners and consultants as they undertake or critically review landform design studies have been provided in Loch et al. (2025) and Hancock et al. (2025). The authors believe there is a growing recognition of the need for formalised training to build professional capacity regarding specialised erosion modelling and landform design skills.

3.3 Interrelated objectives

Alongside the intent that a landform design avoids rill initiation, there are other interrelated objectives that will support a stable landform design.

The intended PMLU informs the rate and type of groundcover (vegetative or other) that must be achieved. Modelling studies can assess a design's ability to remain stable at required groundcover rates. Sensitivity analyses can be undertaken to predict landform performance across a variety of groundcover rates. For example, modelling a scenario where the landform has no or very low rates of vegetation can highlight the importance of vegetation cover for landform stability and identify hot-spot areas on a landform that are prone to erosion (Hancock et al. 2025). Water management strategies, such as the removal of berms once vegetation is established, can also be assessed by the modelling study.

3.4 Relevance to closure criteria

Establishing acceptable erosion rates for a final landform is a common concern raised by stakeholders as they develop completion criteria for quantifying rehabilitation success.

The target erosion rates used to inform the landform design process and articulated by Loch et al. (2025) are not intended as final completion criteria but are useful to inform their development in the modelling phase.

Once a landform is constructed and revegetated, accurately measuring sediment loss that is representative of conditions can be challenging (Nicosia et al. 2024; Boix-Fayos et al. 2006). A practical approach to developing completion criteria may involve combining observational data of erosion features, such as measuring rill/gully width, length and depth or heights of pedestals for sheet erosion (Hancock et al. 2025) from multiple locations across the landform with complementary indicators, such as constructed slope gradients, groundcover levels and surface water quality, to demonstrate erosional stability effectively. Terrestrial lidar and UAV (unmanned aerial vehicle) data at appropriate resolution can be used to measure and analyse erosion on slopes and to verify whether the landform was constructed in accordance with its design (Neugirg et al. 2014; Pratt & Mangan 2013).

3.5 Translation of design into reality

To ensure the landform performs as designed, there will be several assumptions contained within the design specifications that must be achieved during the construction and post-construction phases.

Final landforms must be constructed in strict accordance with design specifications. Implementing a comprehensive program to enforce quality assurance (QA) and quality control (QC) processes during construction is essential to achieving this goal. For instance, soil and mine waste sampling regimes verify material properties and guide material placement, as-built surveys confirm compliance with design features such as slope geometry, and document control procedures uphold QA/QC requirements.

Post construction, monitoring and maintenance is necessary to achieve required groundcover rates, repair or remediate erosion and ensure the PMLU is achieved. It is challenging to avoid the initiation of erosional features on a constructed landform, particularly during the high-risk period where the surface transitions to appropriate levels of vegetative cover and/or states of self-armouring. The timing of rain events and rainfall intensity will impact erosional stability. Predictive erosion models indicate the location and density of erosion features and the rate of sediment detachment (and deposition) associated with a design. Monitoring post construction plays an important role in testing the predicted performance of the design by identifying erosion trends and whether the landform has progressed satisfactorily past the high-risk period and is on a trajectory towards stability. Monitoring is critical to prioritise remediation works and demonstrate the achievement of a stable landform surface (Hancock et al. 2025; Loch et al. 2025).

4 Conclusion

An optimised landform design which seeks to avoid rill initiation and prevent gully development lays a strong foundation for successful achievement of a stable landform once constructed.

Underlying the principles and practices discussed in this paper are the assertions that gully erosion is a critical failure point for landform stability, exposure of underlying contaminants is not acceptable, and rills are the precursor to gullies.

In particular, rill initiation is considered a critical event because it represents the point at which there is a rapid increase in the rate of soil loss, development of increasing numbers of erosional features, presents a greater risk of landform instability, increasing cost to repair erosion features, escalating potential to expose encapsulated, hazardous material and an increasing risk that the PMLU will not be achieved.

Modelling studies are useful to inform and optimise the landform design but require a clear understanding of the underlying hydrological and sediment transport processes used by a specific model, soil physical functions and erosional processes and the erosion rate at which the critical threshold of rill initiation will commence.

There are challenges in selecting an appropriate target rate of erosion for use in modelling studies. This is because there are no universally accepted erosion modelling targets applicable to mine rehabilitation. A long-term average erosion rate of 4 t/ha/yr for a post-mine landform slope, weighted accordingly to site-specific risk, is proposed for modelling purposes only. This rate is not presented as applicable for setting completion criteria but can be used along with other measured and observed data to inform criteria that demonstrate if a stable post-mining landform has been achieved.

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