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Parametric landform evolution modelling assessment of conceptual batter designs for mine closure trials

Ye Ma [a,*], Oliver Dudley [a], Byron House [a], Mike Liu [a]

[a] *Geosyntec Consultants, Australia*

Abstract

This study uses landform evolution modelling (LEM) to test how different batter geometries influence soil capping surface performance under a range of rainfall conditions. Using the State Space Soil Production and Assessment Model (SSSPAM) modelling package, we assess batter trial concepts that incorporate alternative slope forms and surface controls, such as linear slopes, contour bunds and concave profile elements.

The work is structured around a parametric sensitivity framework. Key geometry inputs are varied to generate a suite of design variants. These variants are then evaluated under multiple rainfall scenarios that span different intensities and storm durations to represent a range of wet season events and stress conditions. Model outputs are assessed in terms of predicted erosion and deposition patterns through time.

Overall, the study provides a modelling-based comparison of batter shape options under various climatic forcing. The results could provide the discussion on trial design optimisation and risk-informed decision-making, and the workflow is transferable to mine closure landforms and other engineered slopes where rainfall-driven erosion is a critical performance risk.

Keywords: *landform evolution modelling, batter geometry, rainfall events*

1 Introduction

Mine closure designs are required to remain safe, stable and non-polluting over long time frames; hundreds to thousands of years beyond closure. Landform studies are therefore necessary to understand the progressive development of surface erosion, as well as rill and gully incision, and to provide a basis for assessing whether a landform is likely to degrade or stabilise over time. While erosion modelling is widely used to support landform design, existing applications often rely on generic parameterisation and limited evaluation of how batter geometry interacts with site-specific erodibility and rainfall variability. Insufficient parameter definition and lack of linkage to material properties remain key limitations in many modelling studies.

In particular, batter landform assessment is a critical component of erosion control and long-term stability design, as batter slopes are typically steeper than surrounding surfaces and are consequently more vulnerable to run-off erosion, rill and gully formation, and ongoing sediment/soil loss over time. This study applies landform evolution modelling (LEM) to evaluate the transient performance of alternative batter geometries under various rainfall conditions. The assessment focuses on how batter shape and surface control features influence erosion processes, run-off concentration and overall landform stability. A parametric sensitivity framework was adopted to systematically vary key geometric configurations, including linear slopes, contour bunds and concave profiles, and evaluate their response to a range of rainfall intensities and storm durations. This study addresses this gap by applying a structured parametric LEM framework to explicitly evaluate the interaction between batter geometry, erodibility and rainfall temporal distribution, with emphasis on isolating geometry-driven erosion responses under controlled assumptions.

* Corresponding author. Email address: ye.ma@redearthengineering.com.au

The influence of batter geometry on landform performance has been a longstanding question in mine closure and rehabilitation design. Previous studies, including Hancock (2004), demonstrated that slope profile geometry can significantly affect erosion behaviour and sediment transport processes. Building on this understanding, 3 representative batter geometry scenarios were developed in this study to assess potential improvements in erosion performance. These scenarios are:

1. conventional planar batter (baseline, linear slope) – uniform, linear batter with a constant slope angle and no surface controls, used as a reference case to evaluate run-off concentration, erosion patterns and incision risk under multiple rainfall scenarios
2. concave batter with benches – batter geometry incorporates concave slope profiles and intermittent benches to disrupt run-off pathways and reduce erosion potential
3. enhanced surface-control batter (contour bunds to create microcatchments) – builds on the contour bunds' geometry by adding microcatchment features and surface microtopography to further manage run-off routing and localised erosion for evaluation of erosion/deposition behaviour and long-term stability under wet season conditions. The conceptual model of those conditions is illustrated in Figure 1.

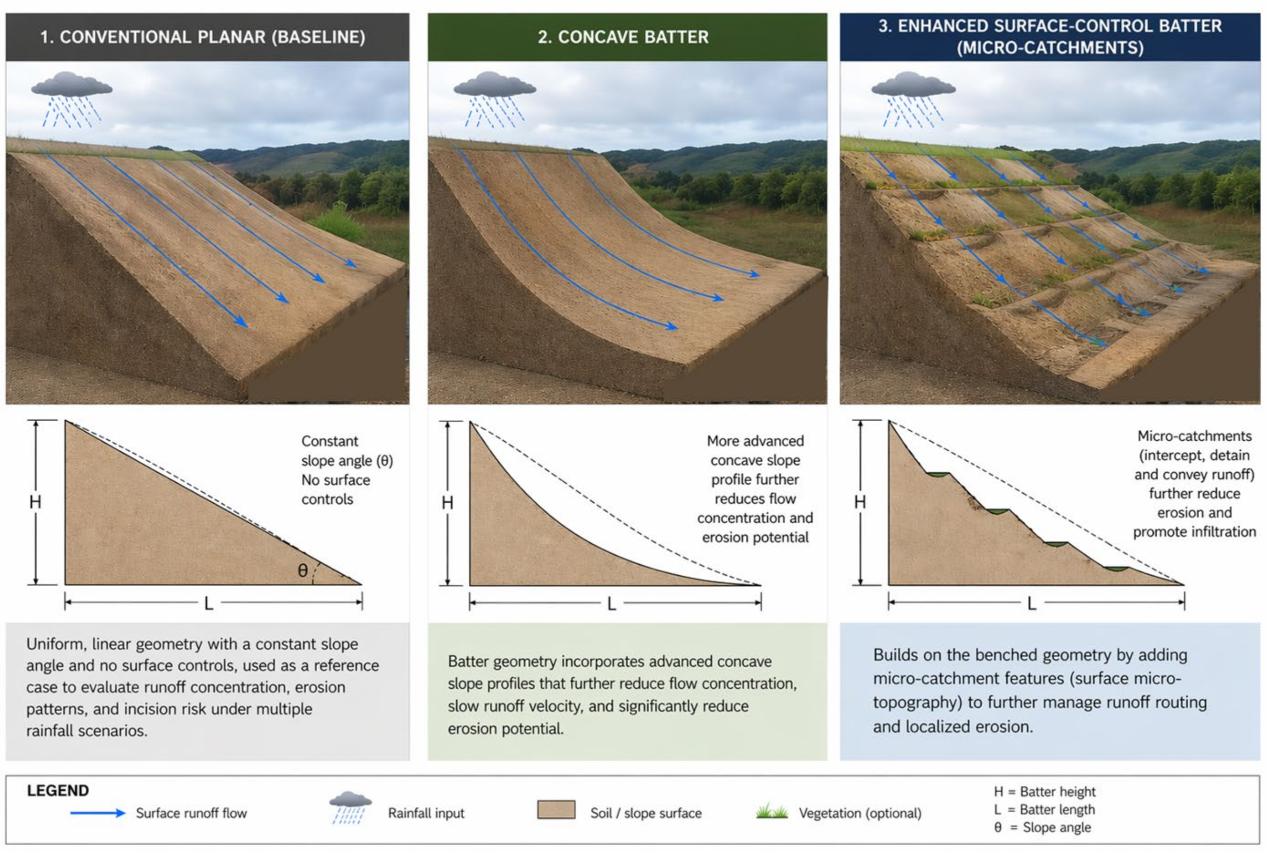

Figure 1 The 3 slope batter geometries assessed in the modelling study

2 Landform evolution modelling methodology

The State Space Soil Production and Assessment Model (SSSPAM) is an advanced LEM software that could be applied to simulate rainfall events and long-term terrain changes by integrating surface erosion processes with subsurface soil development. The SSSPAM program was developed by Welivitiya et al. (2016, 2019, 2025). SSSPAM shows a key innovation in landform modelling. It couples soil profile (pedogenesis) evolution with traditional landform erosion and deposition processes in a single framework. This capability allows

SSSPAM to track soil texture and structure changes in multiple layers over time; something earlier LEM models typically neglected by assuming a static or single-layer soil. As a result, SSSPAM can analyse how subsurface changes (e.g. weathering, armouring) feed back into surface erosion rates and landform stability (Welivitiya 2024). The model employs a state space matrix methodology to streamline complex process equations, achieving computational efficiency despite its detailed physics. In essence, SSSPAM can simulate fluvial erosion (both detachment and transport-limited), sediment deposition, diffusive processes (rain splash, soil creep, small slides), surface armouring and depth-dependent weathering concurrently. This integrated approach enables more realistic predictions of landscape evolution, especially in scenarios where the soil's evolving properties significantly influence erosion dynamics. The transport capacity at a pixel (node) T_c is given by Welivitiya et al. (2019) as:

$$T_c = K\ eq^{\alpha_1} S^{a_2}\ T \tag{1}$$

where:

e	=	the erodibility factor
q	=	the discharge per unit width (m^3 s^{-1} m^{-1}) at the pixel
S	=	the slope gradient (m m^{-1})
a_1 and a_2	=	exponents governing the erosion process
T	=	the length of the timestep used.

The limiting parameter, *K*, determines the maximum volume of erosion that potentially could occur at the pixel.

Discharge per unit width, q, is derived from contributing area and run-off generation as:

$$\boldsymbol{q} = \frac{\boldsymbol{rA_C}}{\boldsymbol{\omega}} \tag{2}$$

where:

r	=	run-off excess generation (m^3 s^{-1} m^{-2})
A_C	=	contributing area (m^2) of that pixel
ω	=	the flow width (m) at the pixel.

The flow chart of the LEM model approach is summarised in Figure 2, which presents an integrated application framework for the SSSPAM LEM model within mine closure and rehabilitation planning. It demonstrates how key input datasets, including digital elevation models (DEM), climate and rainfall conditions, soil and material properties (vegetation), and rehabilitation design parameters, are incorporated into geomorphic analysis and erosion/deposition modelling processes. The framework also considers soil profile evolution, and topographic updates over time, allowing simulation of long-term landscape responses under variable environmental conditions. Through iterative calibration, sensitivity analysis and scenario testing, the SSSPAM model can be used to assess landform stability, erosion risk, sediment yield and rehabilitation performance. This supports risk-informed landform closure design, optimisation of surface controls and cover systems, and development of sustainable post-mining landforms that meet long-term closure objectives.

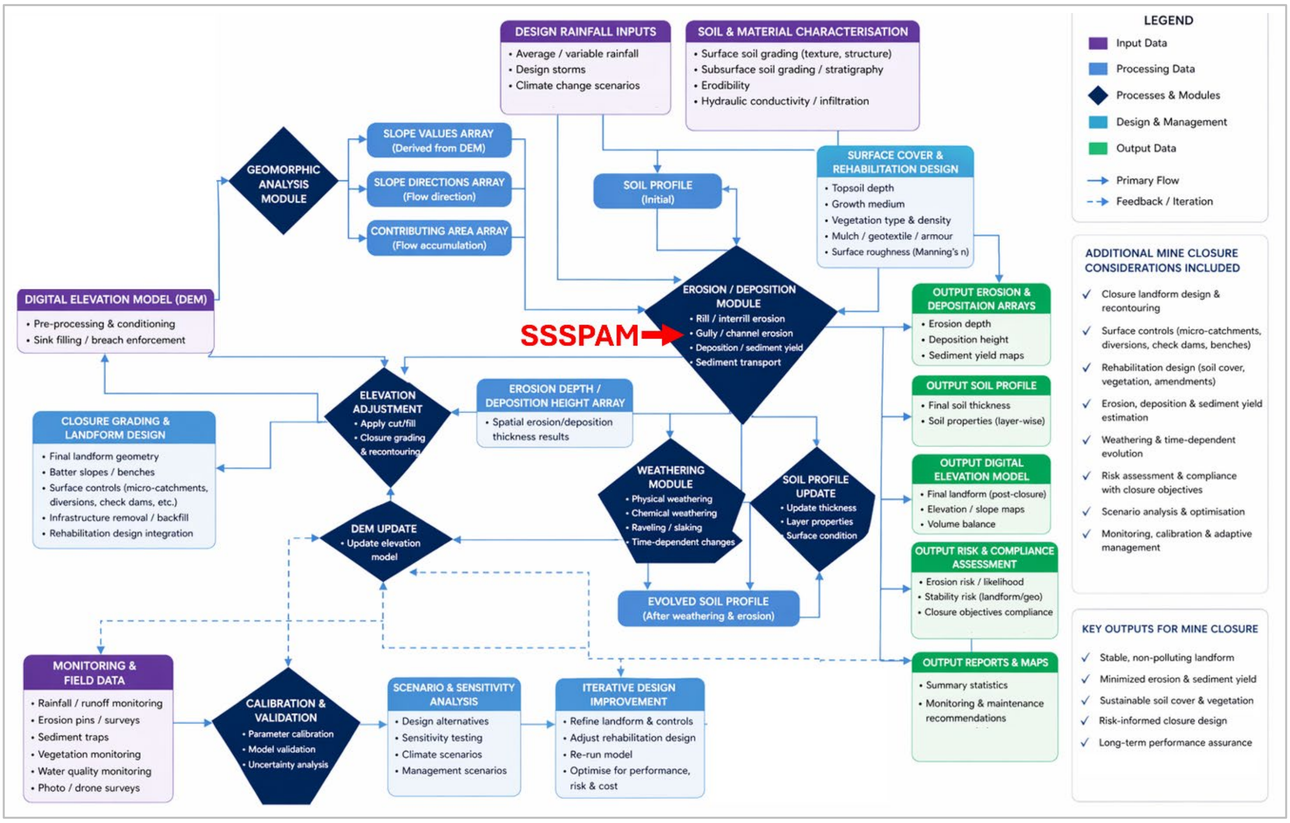

Figure 2 Flow diagram of State Space Soil Production and Assessment Model (SSSPAM) operations (modified from Welivitiya et al. 2021)

In relation to batter slope design, both for operational batters and the final closure landform of embankment areas, as well as tailings or pond surfaces, 3 principal geometric profiles are commonly considered. These slope configurations are frequently evaluated and referenced throughout pre-feasibility, feasibility and detailed design stages within both consulting and operational environments. The linear batter profile has been studied in the past by various studies. Slope angles ranging from 1:3 to 1:5 are commonly suggested, depending on regulatory requirements or operational space needs. However, erosion behaviour is highly site-specific and largely depends on the erodibility of the soil materials and the dispersive characteristics of the capping layer (Hancock 2004; Hancock et al. 2008). The use of concave batter profiles in mine rehabilitation has often been adopted as a preferred design approach, however, applying these shapes without supporting erodibility testing or erosion modelling can lead to poor outcomes. While concave slopes can reduce run-off concentration and erosion in some settings, they are not universally effective and may provide little benefit or still result in unstable landforms if site-specific material properties are not considered. Case studies have shown that successful designs often require additional controls such as surface cover, material amendments and water management measures. Therefore, concave profiles should be supported by robust erosion assessment rather than treated as a generic best-practice solution by Howard et al. (2011). The contour bunds concept has been evaluated through 5 years of post-closure performance monitoring at a mine (Gregory et al. 2019), providing a practical case study for mine rehabilitation design. Uncontrolled surface water run-off and poor revegetation were identified as 2 of the key closure risks for this project, as both factors can significantly affect long-term landform stability and rehabilitation success. Contour bunds were implemented as a surface water management measure to reduce run-off velocity, improve water retention and create more favourable conditions for vegetation establishment. The monitoring results highlight the importance of integrating erosion control and revegetation strategies into closure planning and demonstrate the value of long-term performance data in refining landform design approaches (Gregory et al. 2019). In this study, 3 slope geometry profiles were developed to enable a comparative erosion assessment, as shown in Figure 3.

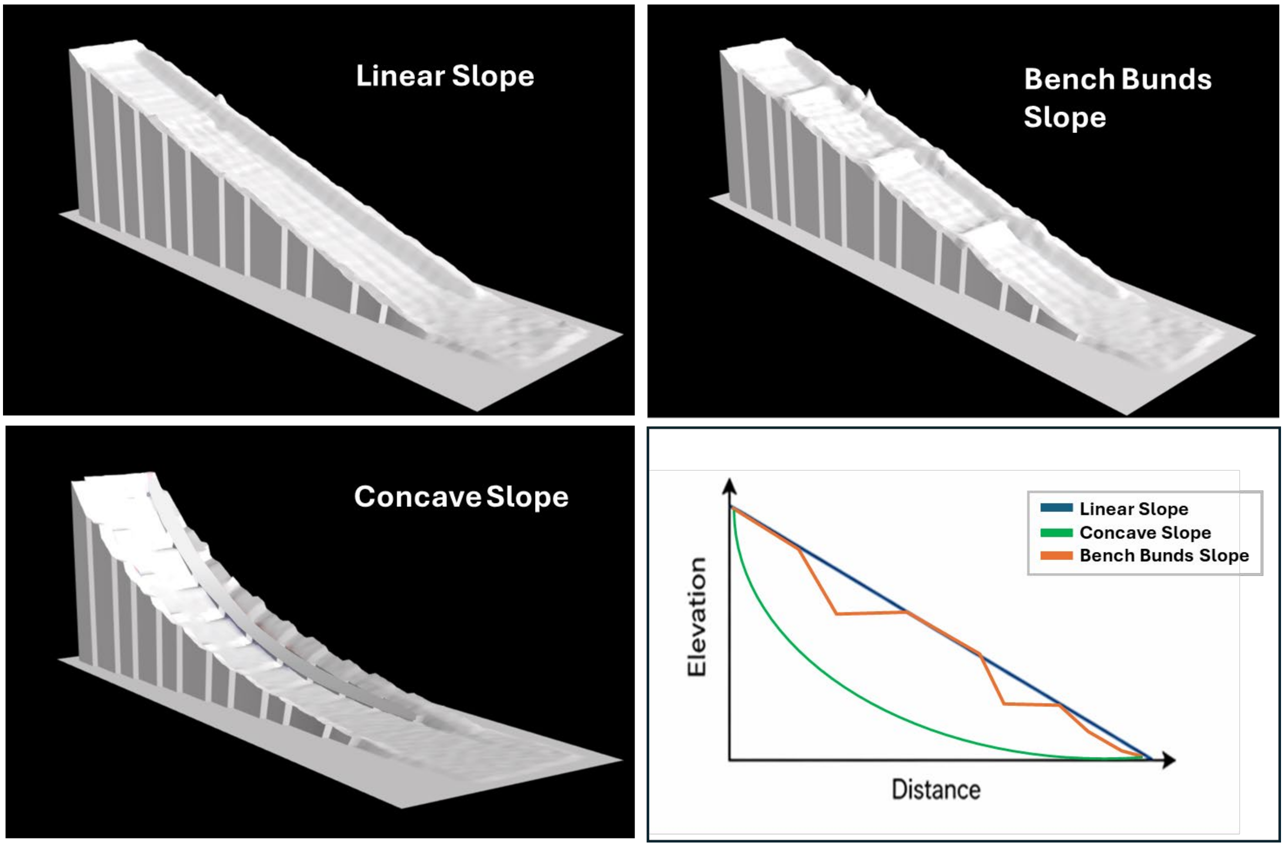

Figure 3 The 3 batter slope profiles being evaluated in this study

3 Parametric study results and discussion

These 3 slope geometries were evaluated under the various rainfall conditions to enable a consistent comparison of erosion performance. The model was simulated over a 2-year period (tropical monsoonal climate rainfall condition), with monthly updates to ground surface elevation generated throughout the analysis. Key outputs included cumulative erosion, deposition rates and erosion depth distributions.

Many parameters can influence simulated erosion outcomes; however, this study focuses on erodibility as it is widely recognised as one of the most sensitive and site-specific inputs for LEM. Erodibility has been extensively investigated through laboratory flume testing, rainfall simulator experiments and long-term field-monitoring programs. A well-calibrated erodibility parameter is considered a critical requirement for validating the LEM model and establishing confidence in its use for the prediction, design and performance assessment of closure landforms. Accordingly, a series of progressively increasing erodibility values were first tested to evaluate model sensitivity to this parameter (Table 1). A relatively high erodibility parameter was then intentionally adopted to amplify differences between the 3 slope configurations to better assess the influence of geometry on erosion response. The model used a 0.5 m mesh grid resolution. The overall average slope gradient was approximately 1V:5H, with each geometry designed to generally maintain this same gradient so that the study focused primarily on the effect of profile shape variation rather than slope angle differences.

Table 1 summarises the 19 LEM simulations undertaken to assess the effects of soil erodibility, batter geometry and rainfall pattern on erosion performance over a 2-year period. Simulations 1 to 8 evaluate the sensitivity of a linear 1V:5H batter slope to a range of erodibility values, while simulations 9 and 10 compare alternative slope geometries (bunds and concave) using the relative high erodibility case. Simulations 11 to 19 examine the combined influence of modified rainfall patterns across the linear, bunded and concave batter configurations, all using an erodibility value of 8.0. Erodibility parameters were selected to represent a conceptual range of surface materials, including low erodibility compacted soils, moderate erodibility rehabilitated growth media and highly erodible dispersive or fine-grained materials.

The selected range (0.08 to 8.0) is not intended to represent calibrated site-specific values but rather to span the spectrum between stable, vegetated surfaces and highly erodible waste materials identified in post-mining landforms. Such use of generic parameter ranges for sensitivity analysis is consistent with early-stage modelling approaches:

- 0.08–0.6 represents compacted or partially stabilised surfaces with low erosion potential
- 3.8–8.0 represents highly erodible fine-grained or dispersive materials typical of unconsolidated waste or poorly established rehabilitation surfaces.

Table 1 List of the simulation runs

Simulation	Scenarios	Parameters
1	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 0.08
2	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 0.2
3	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 0.4
4	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 0.6
5	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 3.8
6	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 4.5
7	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 6.8
8	Batter with linear slope 1V:5H, 2 years daily rainfall	erodibility is 8.0
9	Batter with bunds slope 1V:5H, 2 years daily rainfall	erodibility is 8.0
10	Batter with concave slope, 2 years daily rainfall	erodibility is 8.0
11	Batter with linear slope 1V:5H, 2 years daily rainfall pattern 1	erodibility is 8.0
12	Batter with linear slope 1V:5H, 2 years daily rainfall pattern 2	erodibility is 8.0
13	Batter with linear slope 1V:5H, 2 years daily rainfall pattern 3	erodibility is 8.0
14	Batter with bunds slope 1V:5H, 2 years daily rainfall pattern 1	erodibility is 8.0
15	Batter with bunds slope 1V:5H, 2 years daily rainfall pattern 2	erodibility is 8.0
16	Batter with bunds slope 1V:5H, 2 years daily rainfall pattern 3	erodibility is 8.0
17	Batter with concave slope, 2 years daily rainfall pattern 1	erodibility is 8.0
18	Batter with concave slope, 2 years daily rainfall pattern 2	erodibility is 8.0
19	Batter with concave slope, 2 years daily rainfall pattern 3	erodibility is 8.0

Manning's roughness coefficient (*n*) parameter for a range of surface conditions is commonly used in erosion and run-off modelling. Lower Manning roughness coefficient (*n*) values apply to smooth, compacted surfaces with minimal flow resistance, while higher Manning roughness coefficient (*n*) values represent rougher or vegetated surfaces that slow run-off and increase hydraulic resistance (Table 2). In this study, a Manning roughness coefficient of 0.1 is applied to all 19 LEM simulations. Although surface roughness may vary spatially, a value of 0.1 was selected for all the 19 LEM simulations to isolate the model's sensitivity to erodibility parameter.

Table 2 Manning's coefficient applied for various conditions

Surface condition	Typical Manning's coefficient (*n*)
Smooth compacted clay cover	0.015–0.030
Bare graded soil/compacted earth	0.020–0.050
Rough ripped soil surface	0.040–0.080
Topsoil with sparse grass	0.060–0.120
Dense grassed cover	0.100–0.250
Rock mulch/rip rap mixed soil	0.035–0.100
Shrub/vegetated rehabilitation cover	0.100–0.30

3.1 Parameter sensitivity study

Figure 4 illustrates the influence of soil erodibility on predicted erosion responses over the 2-year simulation period. Figure 4a presents the cumulative rainfall record used in the modelling, showing distinct rainfall clusters occurring mainly between 0.4 to 0.8 years and 1.45 to 1.80 years, separated by a prolonged dry interval with minimal rainfall. Total cumulative rainfall reaches approximately 4,400 mm by the end of the simulation. Figure 4b shows the corresponding cumulative erosion volumes for a range of soil erodibility values. Lower erodibility values (0.08–0.6) generate relatively minor erosion responses, with erosion volumes generally remaining below 25 m^3, whereas higher erodibility values (3.8–8.0) result in substantially greater erosion, with final cumulative erosion volumes ranging from approximately 60 to more than 90 m^3. The highest erosion occurs for the erodibility value of 8.0, demonstrating the strong sensitivity of landform performance to material erodibility. Overall, this highlights that soil erodibility is a dominant control on erosion magnitude, particularly during periods of intense rainfall. The purpose of this analysis is to quantify the magnitude of sensitivity and to establish the relative influence of erodibility compared to geometry and rainfall variability. The results demonstrate that erodibility dominates erosion magnitude, with variations in parameter values resulting in a > threefold to fivefold increase in predicted erosion volumes, significantly exceeding the influence of geometry.

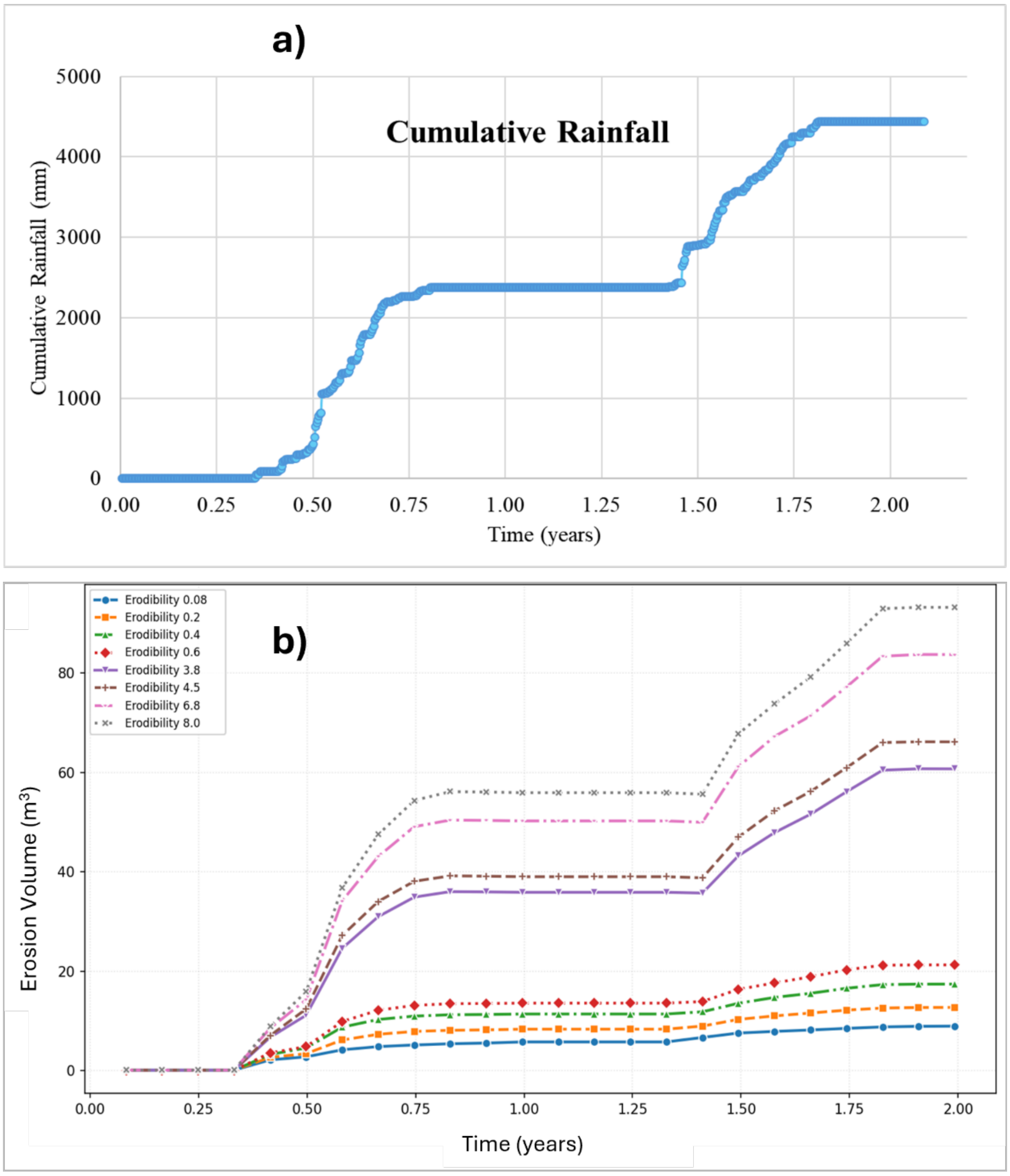

Figure 4 (a) Cumulative rainfall; (b) Cumulative erosion under various erodibility values

3.2 Landform surface elevation for 3 batter slope geometries

Figure 5 compares 3 landform surface configurations used for erosion assessment and mine closure landform design. The top left panel in Figure 5 presents shows a linear slope, representing a conventional uniform planar batter with a constant gradient. The top right panel in Figure 5 presents a bench bunds slope, where intermediate bunds or benches are incorporated to interrupt run-off pathways and reduce flow concentration. The bottom left panel in Figure 5 illustrates a concave slope, featuring a gradually flattening profile toward the toe to reduce run-off velocity and erosion potential. The effective erosion in mm/year is summarised for each run. In comparison with the influence of erodibility, the overall erosion behaviour across the 3 different slope configurations is less significant than the variation caused by changes in erodibility.

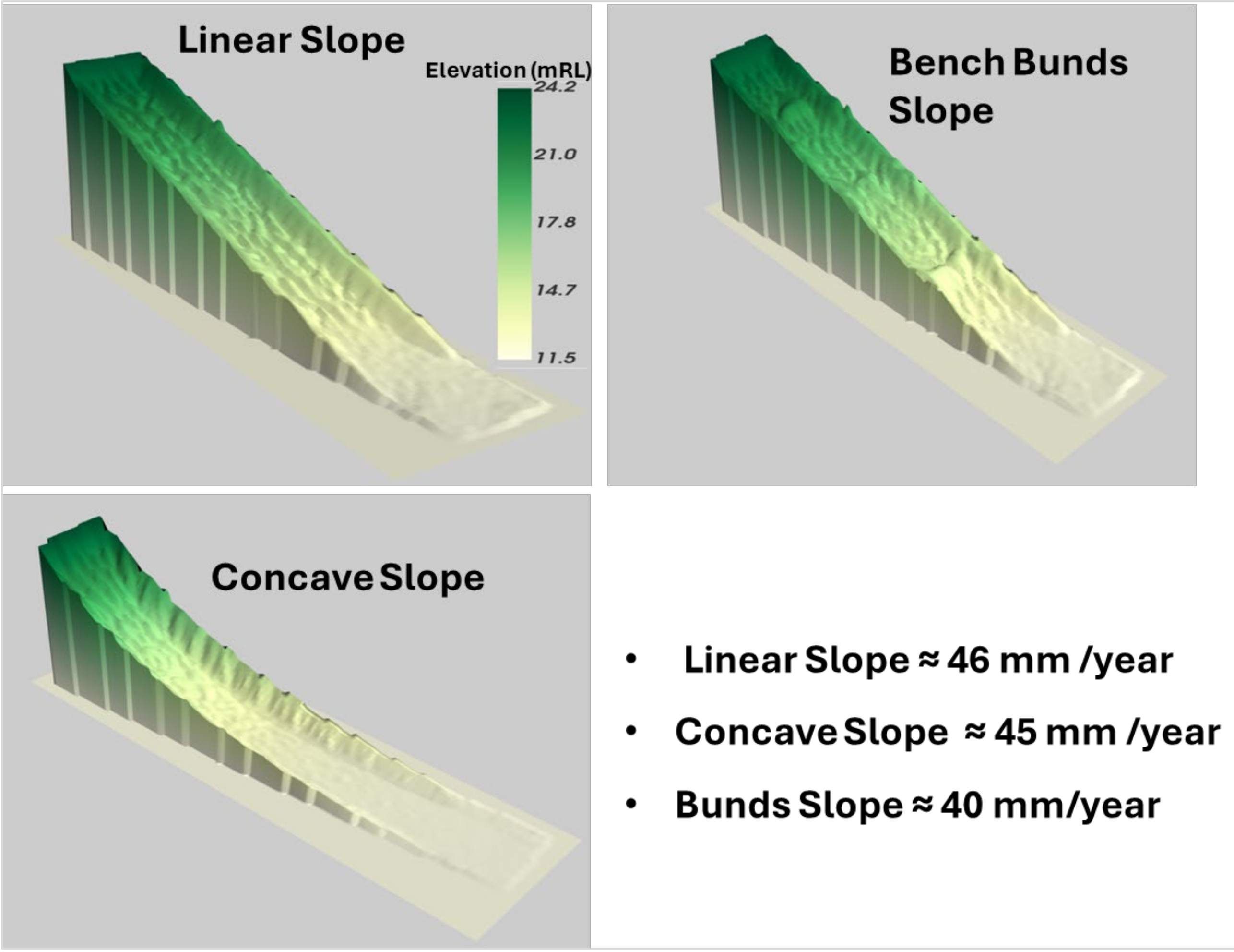

Figure 5 The 3 batter slope profiles after 2 years of landform evolution modelling simulation

3.3 Rainfall impact on the landform evolution model

To evaluate the influence of rainfall distribution on LEM simulations, 3 additional rainfall scenarios were developed and applied, as shown in Figure 6. These scenarios were designed to assess how changes in rainfall intensity and temporal pattern may affect erosion response. Rainfall pattern 1 increases the top 10% of daily rainfall events by 20%, while rainfall on the remaining days is proportionally reduced so that total annual rainfall remains unchanged. Rainfall pattern 2 decreases the top 10% of daily rainfall events by 20%, with rainfall on all other days increased proportionally to maintain the same annual rainfall total. Rainfall pattern 3 applies a uniform 20% increase across all rainfall events, resulting in an overall 20% increase in total rainfall.

Figure 6 compares the applied rainfall scenarios and their corresponding erosion responses over the 2-year simulation period. Figure 6a presents cumulative rainfall for the base case and 3 modified rainfall patterns. The base case, and rainfall patterns 1 and 2, generate similar total rainfall depths of approximately 4,400 to 4,500 mm, but differ in the timing, distribution and intensity of daily rainfall events. In contrast, rainfall pattern 3 applies a uniform 20% increase to all rainfall events, resulting in a higher cumulative total of approximately 5,300 mm by the end of the simulation. Distinct rainfall clusters occur around 0.5 to 0.8 years and 1.5 to 1.8 years, separated by relatively dry periods with limited rainfall accumulation.

Figure 6b shows the cumulative erosion volume for the 3 batter geometries (linear, bunds and concave) under the same rainfall scenarios. Erosion increases rapidly during major rainfall periods and remains relatively stable during dry intervals, confirming that erosion is strongly event driven. Across most scenarios, the concave slope geometry records the highest erosion volumes, while the bunded slope geometry generally reduces erosion relative to the conventional linear slope. The greatest erosion occurs under rainfall pattern 3, reaching approximately 105 to 110 m³, whereas the lower rainfall scenarios remain below approximately 95 m³. Overall, this demonstrates that both rainfall magnitude and temporal distribution are controls on long-term erosion performance. Similar findings regarding the importance of rainfall variability and slope design have been reported in previous studies by Lowry et al. (2024) and Hancock et al. (2017).

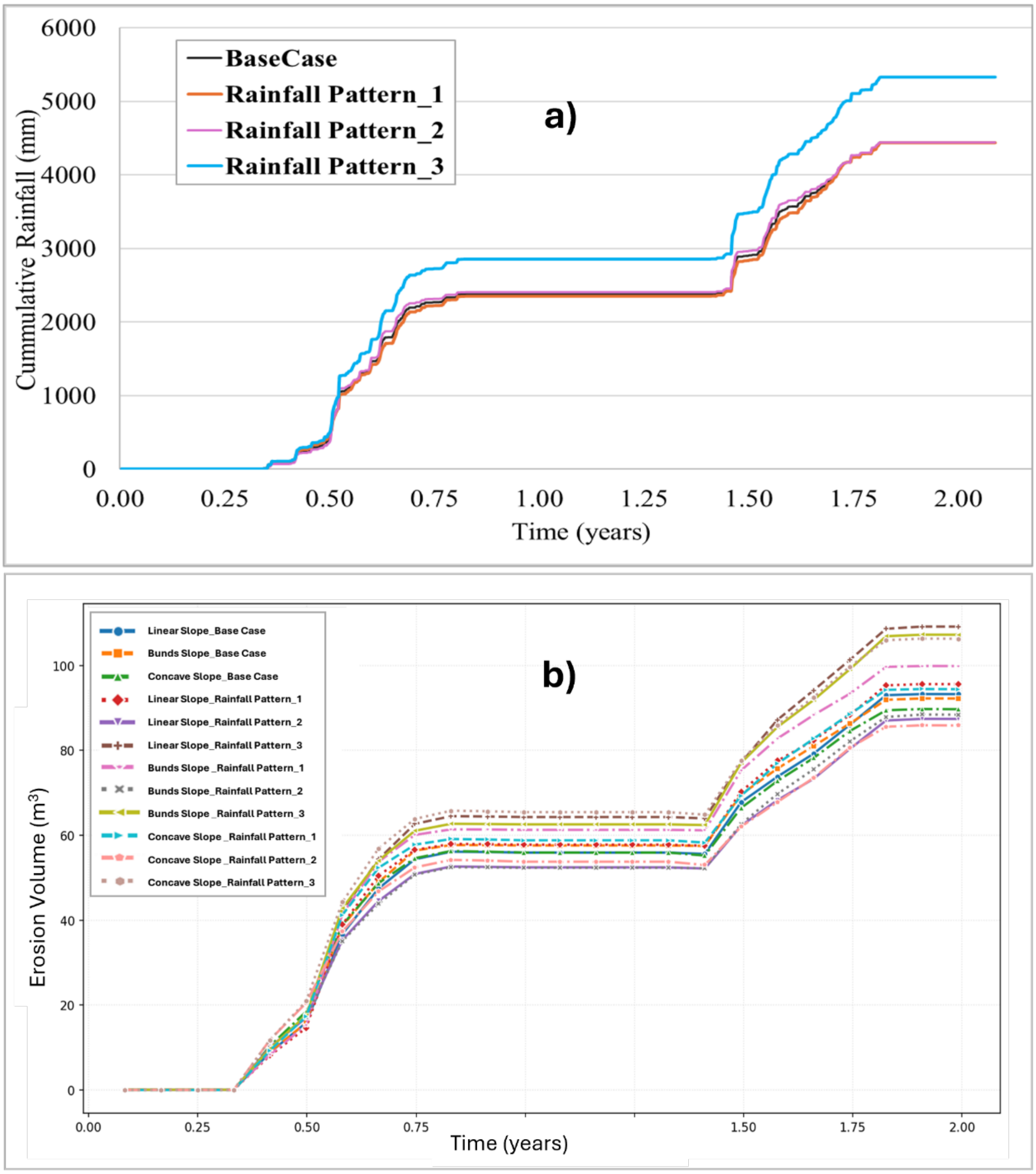

Figure 6 (a) Cumulative rainfall for 4 different patterns; (b) Compares the applied rainfall scenarios and their corresponding erosion responses over the 2-year simulation period

4 Conclusion

The parametric study demonstrates that the erosion response predicted by landform evolution modelling (LEM) model is highly sensitive to the selected erodibility parameter, particularly during periods of concentrated rainfall. Higher erodibility values produced substantially greater cumulative erosion volumes, confirming that reliable calibration of this parameter is critical for realistic landform performance assessment. The results also indicate that erosion processes are strongly event driven, with the majority of material loss occurring during high-intensity rainfall clusters rather than uniformly over time. This highlights the importance of accurately representing both surface material properties and rainfall temporal patterns within the modelling framework. This study demonstrates that landform erosion behaviour is governed primarily by material erodibility, with geometry and rainfall distribution acting as secondary controls. Across the tested scenarios, increasing erodibility produced a greater than threefold increase in cumulative erosion, while changes in batter geometry resulted in comparatively smaller variations. Among the geometries evaluated, contour bund configurations consistently reduced erosion relative to linear and concave profiles, highlighting their effectiveness in disrupting flow concentration and supporting landform stability. However, concave profiles did not universally improve performance, reinforcing that geometry alone cannot compensate for high erodibility materials.

The study also found that the adopted erodibility parameter cannot be considered independently of model resolution or numerical set-up. Previous research has shown that erodibility values may require scaling when different digital elevation model (DEM) grid resolutions are used, as finer grids can capture more detailed flow concentration pathways, slope variability and incision processes, whereas coarser grids may smooth terrain features and suppress erosion response (Hancock 2005). Similarly, the selected computational timestep may influence run-off routing, sediment transport rates and rainfall event representation, meaning erodibility values calibrated for one temporal resolution may not be directly transferable to another.

Accordingly, further work is recommended before applying the calibrated parameters for final design or comparative assessment. This should include a systematic sensitivity study examining the influence of DEM cell size (e.g. 0.25, 0.5, 1 and 2 m resolution) on predicted erosion rates and determining whether erodibility scaling factors are required for consistent results across resolutions (Welivitiya & Hancock 2022). Additional testing should also assess the impact of simulation timestep selection (e.g. hourly, daily or event-based) on erosion predictions and whether parameter adjustment is needed to maintain numerical stability and physical realism (Welivitiya & Hancok 2022).

Where possible, future calibration should be supported by laboratory data – along with field-monitoring data such as drone-based topographic surveys, erosion pin measurements, sediment yield observations or rainfall run-off monitoring – to link modelled erosion behaviour with observed site performance. Establishing a robust scaling relationship for erodibility across spatial and temporal resolutions would significantly improve confidence in the LEM model as a design and risk assessment tool for mine closure landforms and engineered batter systems.

Acknowledgement

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References

Gregory, S, Mackenzie, S & Bow, B 2019, 'The Pardoo mine: closure planning, implementation and five years of performance monitoring data', in AB Fourie & M Tibbett (eds), *Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 457–470, https://doi.org/10.36487/ACG_rep/1915_38_Gregory

Hancock, GR 2004, 'The use of landscape evolution models in mining rehabilitation design', *Environmental Geology*, vol. 46, no. 5, pp. 561–573.

Hancock, GR 2005, 'The use of digital elevation models in the identification and characterization of catchments over different grid scales', *Hydrological Processes: An International Journal*, vol. 19, no. 9, pp. 1727–1749.

Hancock, GR, Crawter, D, Fityus, SG, Chandler, J & Wells, T 2008, 'The measurement and modelling of rill erosion at angle of repose slopes in mine spoil', *Earth Surface Processes and Landforms*, vol. 33, no. 7, pp. 1006–1020.

Hancock, G. R., Verdon-Kidd, D., & Lowry, J. B. C 2017, 'Soil erosion predictions from a landscape evolution model–An assessment of a post-mining landform using spatial climate change analogues', *Science of the Total Environment*, 601, pp. 109–121.

Howard, EJ, Loch, RJ & Vacher, CA 2011, 'Evolution of landform design concepts', *Mining Technology*, vol. 120, no. 2, pp. 112–117.

Lowry, J, Saynor, M, Hancock, GR & Coulthard, T 2024, 'Using a landform evolution model to model the effect of extreme rainfall events on the geomorphic stability of a rehabilitated landform', in AB Fourie, M Tibbett & G Boggs (eds), *Mine Closure 2024: Proceedings of the 17th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 59–70, https://doi.org/10.36487/ACG_repo/2415_02

Welivitiya, WDP, Willgoose, GR, Hancock, GR & Cohen, S 2016, 'Exploring the sensitivity on a soil area-slope-grading relationship to changes in process parameters using a pedogenesis model', *Earth Surface Dynamics*, vol. 4, no. 3, pp. 607–625.

Welivitiya, WDP, Willgoose, GR & Hancock, GR 2019, 'A coupled soilscape–landform evolution model: model formulation and initial results', *Earth Surface Dynamics*, vol. 7, no. 2, pp. 591–607.

Welivitiya, WDP, Willgoose, GR & Hancock, GR 2021, 'Evaluating a new landform evolution model: a case study using a proposed mine rehabilitation landform', *Earth Surface Processes and Landforms*, vol. 46, no. 11, pp. 2298–2314.

Welivitiya, WDP & Hancock, GR 2022, 'Calibration and validation of the SSSPAM coupled soilscape–landform evolution model for simulating short-term gully development on a post-mining landform', *Earth Surface Processes and Landforms*, vol. 47, no. 11, pp. 2779–2795.

Welivitiya, WDP & Hancock, GR 2024, 'Quantifying mine waste rock physical weathering rate and processes for improved geomorphic post-mining landforms', *Geomorphology*, vol. 463, article 109357.

Welivitiya, WDP & Willgoose, GR Hancock, GR & Senanayake, IP 2025, 'Modelling hillslope soil profiles using a coupled pedogenesis and landform evolution model', *Soil Advances*, 100074.