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Establishing trial batter studies to calibrate landform evolution models for post-mining landform relinquishment

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Abstract

Achieving successful relinquishment of post-mining tailings storage facility (TSF) landforms requires accurate predictions of long-term stability, erosion rates and vegetation establishment. Landform evolution models (LEMs) are powerful tools for predicting final landform behaviour, but their reliability depends on accurate calibration with laboratory and site-specific derived data. This study presents a structured approach for establishing a full-scale trial batter reshaping and revegetation study to support LEM calibration, ensuring robust, data-driven decision-making for mine closure. The study integrates findings from a large-scale trial batter study conducted between 2021 and 2025 in a tropical mining region of Australia. The trial batter study evaluates 8 potential TSF closure batter designs. There are multiple configurations with varying soil compositions, slope angles and vegetation treatments under real-world climatic and environmental conditions. Performance is monitored using high-resolution unmanned aerial vehicle imagery, lidar surveys, photogrammetry and site inspections. Quantitative measurements of erosion rates are captured from surveys, along with measures of vegetation establishment derived from photogrammetry and analysis of site inspection photographs and observations. These are compared to climatic data from nearby weather stations to understand the various batter treatments to site weather patterns. Analysis of the performance over the 4 years of the study is undertaken to assess trends. This data is then used to parameterise and validate LEM predictions, enabling a detailed comparison between modelled and observed erosion patterns. This research provides a systematic framework for integrating empirical data into LEM applications, improving confidence in their use for post-mining landform design. The findings offer practical guidance for landowners, mine closure practitioners, regulators, and researchers seeking to develop resilient, low-maintenance landforms capable of withstanding long-term environmental processes.

Keywords: *landform evolution modelling, trial batter, SSSPAM, erosion monitoring, revegetation performance*

1 Introduction

The successful relinquishment of post-mining landforms, particularly tailings storage facilities (TSFs), hinges on the ability to predict long-term landscape stability, erosion and vegetation development. As mining operations transition towards closure, there is increasing regulatory and social pressure to demonstrate that reshaped landforms will remain stable and functional over decades or centuries. In the state of Queensland, Australia, a progressive rehabilitation and closure plan (PRCP) is a critical element of the Queensland Government Mined Land and Rehabilitation Plan. The PRCP outlines key requirements for identifying rehabilitation areas, setting milestones and measurable criteria, implementing monitoring programs, and applying for progressive certification and the ultimate relinquishment of mining areas. Within this regulatory framework, landform design and its long-term performance are pivotal, with PRCPs requiring detailed landform designs, construction methodologies, erosion and hydrological assessments, and predictive modelling to support closure objectives.

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Landform evolution models (LEMs) have emerged as powerful tools to simulate the long-term performance of rehabilitated landforms by forecasting processes such as erosion, sediment transport and vegetation dynamics under varying climatic conditions.

However, the reliability of LEM outputs depends heavily on accurate model parameterisation and calibration using empirical data. While LEM proprietary software such as SIBERIA, CAESAR-Lisflood, Water Erosion Prediction Project (WEPP) and Revised Universal Soil Loss Equation (RUSLE) have been widely applied in the mining sector, there remains a critical need for high-quality, site-specific datasets that reflect the complex interactions between soil properties, slope geometry, vegetation and climate. This is particularly true for tropical regions of Australia, where intense rainfall, extreme seasonal variation and diverse vegetation types present unique challenges for mine closure planning.

To address this need, a full-scale trial batter study was established to generate long-term performance data for a range of TSF closure batter designs. Conducted in a tropical mining region of Australia between 2021 and 2025, the study included 8 batter configurations with varying slope angles, soil compositions and revegetation treatments. Erosion and vegetation performance were monitored under site conditions using a suite of remote sensing and ground-based data capturing techniques. These included high-resolution unmanned aerial vehicle (UAV) and lidar surveys, photogrammetry, site inspections and climatic data from a nearby weather station. Additionally, spectral analysis of vegetation cover was used to assess vegetation health and ground cover development over time.

The data generated from this trial batter study will be used to calibrate and validate the LEM. This will enable a more confident prediction of landform performance and support the development of resilient, low-maintenance closure designs that can withstand long-term environmental processes. By integrating empirical monitoring with modelling, this paper provides a robust framework for informing mine closure strategies.

It is important to recognise that the trial batter study and associated modelling presented herein are focused on the batter (slope) scale and are not intended to directly represent full landform- or watershed-scale behaviour. The primary objective of this trial batter study was to isolate and evaluate the performance of different batter design configurations, including material selection, batter geometry and revegetation treatments, under site-specific environmental conditions, and to use these observations to calibrate LEM parameters against measured field performance.

At the TSF-scale, long-term erosion behaviour is also strongly influenced by drainage network development and catchment-scale hydrological processes. As part of the broader closure strategy for the site, the final landform will be regraded to promote controlled run-off via a gently graded surface directing surface water flow toward a centralised closure spillway, thereby limiting flow concentration along batters. Within this overall configuration, individual batters are expected to behave as localised elements where surface treatments and material properties govern erosion response.

Accordingly, the calibration presented in this paper represents an intermediate step in the broader modelling framework. The parameters derived from batter-scale observations are intended to be applied in subsequent catchment-scale LEM simulations, where drainage behaviour and flow concentration can be explicitly considered as part of final landform design and performance assessment.

The trial batter study facilitates direct comparison between multiple design options under consistent environmental conditions. By isolating variables such as batter geometry, capping material and revegetation treatment, the study provides a controlled framework for evaluating performance in terms of erosion resistance, vegetation establishment and constructability. This enables stakeholders to make informed decisions regarding preferred closure design options based on performance, material availability and cost considerations prior to implementation at the full landform scale.

2 Landform evolution model

The long-term erosional stability of post-mining landforms is a critical consideration in mine closure planning. A LEM is a predictive tool used to evaluate the long-term geomorphic stability of landforms. LEMs such as the State Space Soil Production and Assessment Model (SSSPAM), SIBERIA and CEASAR-Lisflood are sophisticated 3D topographic evolution models that simulate long-term changes in a given surface over time due to mass transport processes such as tectonic uplift, fluvial erosion, creep, rain splash and landsliding.

A SSSPAM LEM was employed in this study to simulate the geomorphic development of rehabilitated trial batter study slopes over a timescale. The advantage of an SSSPAM is that it has much of the same functionality as SIBERIA and CAESAR-Lisflood models but includes a surface weathering, armouring and pedogenesis capability allowing both the landscape surface and subsurface evolution to be assessed (Hancock et al. 2025). A LEM provides a predictive framework for evaluating how landforms respond to climatic forces, surface treatments and material properties.

2.1 Model framework: SSSPAM

The SSSPAM is a 3D, process-based, coupled soilscape landform evolution model that simulates changes in landform elevation and soil profile characteristics through time. The model operates on a regular grid digital elevation model (DEM) and requires hydrologically corrected input to ensure realistic flow routing and drainage development.

SSSPAMs explicitly represent fluvial erosion, diffusive processes (such as rain splash and soil creep), sediment deposition, surface armouring and soil weathering within a unified modelling framework. Landform evolution is driven by the balance between sediment transport capacity and sediment load, allowing both detachment-limited and transport-limited erosion processes to be represented (Willgoose et al. 1991a, 1991b). Elevation changes are calculated by updating the DEM iteratively in response to erosion and deposition at each grid cell.

Potential fluvial erosion in SSSPAMs is calculated as a function of discharge per unit width and local slope, following a power law formulation consistent with established landform evolution theory (Welivitiya et al. 2019; Welivitiya & Hancock 2022):

$$E_f = K\, q^{\alpha_1} S^{\alpha_2}\, T \tag{1}$$

where:

E_f = potential fluvial erosion rate per unit width ($m^3\ s^{-1}\ m^{-1}$)

q = discharge per unit width ($m^3\ s^{-1}\ m^{-1}$)

S = local slope in the steepest downslope direction (m/m)

K = erodibility parameter dependent on surface material properties

α_1 = discharge exponent

α_2 = slope exponent

T = model timestep (s).

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

$$q = r\, \frac{A}{w_f} \tag{2}$$

where:

r = run-off excess generation factor ($m\ s^{-1}$)

A = upslope contributing area (m^2)

w_f = flow width, typically equal to the DEM grid resolution (m).

Diffusive erosion is also simulated and represents hillslope processes such as rain splash, soil creep and local bank collapse. Diffusive sediment transport is controlled by slope gradient, a diffusivity coefficient and an optional threshold slope that limits slope steepness.

By coupling surface erosion processes with vertical soil profile evolution and particle size redistribution, SSSPAMs enable simulation of both landform morphology and material evolution over long timescales under varying climatic and surface conditions.

2.2 Parameter derivation

Appropriate parameterisation and calibration are essential for reliable SSSPAM predictions. Parameters governing fluvial erosion, run-off generation, diffusion and soil grading evolution are typically derived using a combination of field data, laboratory testing and calibration against observed erosion behaviour.

Consistent with recommendations by Hancock et al. (2025) and subsequent SSSPAM applications, parameter derivation commonly involves:

- extending observed run-off records using calibrated rainfall run-off models to estimate representative long-term run-off conditions
- calibrating erosion-related parameters (e.g. discharge and slope exponents, erodibility coefficients) using field measured run-off, sediment concentration and particle size distribution data collected from trial landforms or erosion plots
- using the calibrated hydraulic and sediment transport relationships to derive long-term average SSSPAM parameter values representative of the landform materials, surface treatments and climatic regime being modelled.

Where site-specific erosion data are unavailable, parameter values can be estimated from literature-based parameter ranges or the transfer of parameters from analogous landforms; however, such approaches involve increased uncertainty. Accordingly, sensitivity analyses should be undertaken to assess the influence of parameter uncertainty on predicted LEMs.

3 Trial batter study

The trial batter study site detailed in this paper is located in a mining region of Australia with a tropical monsoonal environment characterised by a wet season and a dry season, each lasting approximately 6 months. The dry season poses challenges for vegetation establishment upon closure while the wet poses erosion instability risk due to the intensity and frequency of tropical rainfall.

The soil material used for rehabilitation of the trial batter comprised a mixture of silty sand and sandy silt tailings (with no contaminants), which is highly erodible, and naturally occurring iron-rich lateritic soil commonly known onsite as ‘ironstone’, which, based on site experience, has good properties for erosion stability. The objective of the trial batter study was to assess a suitable batter design for the closure of the site TSF. The actual trial batter slopes’ erosion rates and depths, and vegetation growth, will be used to calibrate a LEM for estimating long-term performance with the overall goal of achieving long-term erosional stability.

The trial batter study was developed to generate site-specific data to support the calibration and validation of a LEM to inform the TSF closure design. Fifteen full-scale trial batter lots were constructed at a site to assess the performance of batter slopes under varying geometrical, material and revegetation configurations. The batters were designed to represent a range of slope geometries, surface treatments and rehabilitation methodologies commonly used or proposed for mine closure in the region. The 2 selected slope angles used for the trial batter are 1V:5H and 1V:3H (18.4° and 11.3°), allowing the study to capture erosion and vegetation response across a gradient of steepness and shear stress conditions. The plant substrate for each batter was either a blend of tailings and weathered ironstone mix or just ironstone. Then a revegetation treatment was added over the substrate, with the following 4 revegetation treatment options:

- Revegetation treatment A: fertiliser and vegetation application
- Revegetation treatment B: mulch, fertiliser and vegetation application.
- Revegetation treatment C: topsoil, fertiliser and vegetation application
- Revegetation treatment D: mulch, topsoil, fertiliser and vegetation application.

All batters were constructed with integrated crest bunds and lateral drains to manage surface water run-off and limit flow concentration. The surface roughness and slope length were controlled during construction to reflect realistic operational closure practices and to provide consistent boundary conditions for comparative analysis. Details regarding trial batter lot design are provided in Table 1.

Table 1 Trial batter lot design configuration

Lot	Slope angle	Revegetation treatment	Substrate
1	1V:5H	A	T& IR* 50:50
2	1V:5H	B	T & IR* 50:50
3	1V:5H	C	T & IR* 50:50
4	1V:5H	D	T & IR* 50:50
5	1V:5H	A	Ironstone
6	1V:5H	B	Ironstone
7	1V:5H	C	Ironstone
8	1V:5H	D	Ironstone
9	1V:5H	A	T & IR* 50:50
10	1V:5H	B	T & IR* 50:50
11	1V:5H	C	T & IR* 50:50
12	1V:5H	D	T & IR* 50:50
13	1V:5H	A	Ironstone
14	1V:5H	B	Ironstone
15	1V:5H	C	Ironstone
16	1V:5H	D	Ironstone

*T & IR denotes tailings and ironstone blend

3.1 Trial batter monitoring

The performance of the trial batter slopes is being assessed through a comprehensive and multiscale monitoring program designed to quantify surface erosion, vegetation establishment and batter stability over time. This monitoring effort provides the empirical dataset necessary for calibrating LEMs and validating slope design performance under the tropical climatic conditions. The monitoring data detailed in this paper were undertaken between 2022 and 2025.

3.1.1 Data collection methods

To capture topographic changes and surface degradation patterns, traditional survey and UAV drone high-resolution lidar surveys are conducted prior to and following the wet season. These surveys provide precise 3D point cloud data from which DEMs are generated, enabling the quantification of vertical change due to erosion, sediment deposition and vegetation growth. The comparison of pre- and post-wet season DEMs allows the identification of net material loss or gain across the trial slopes, which is essential for estimating erosion rates and completing model calibration.

The UAV drone-based surveys use RGB cameras and photogrammetry techniques to produce detailed orthomosaic images, 3D models and supplementary DEMs. These high-resolution orthomosaics support visual inspection, vegetation cover analysis and surface condition mapping. The drone-based photogrammetry also aids in identifying microtopographic features such as rill and gully formation, slope failures and run-off pathways that may not be captured in lidar data alone.

To supplement remote sensing data, quarterly engineering inspections are carried out by an Engineers of Record team. The inspection comprised visual observation and walkovers in sections of each trial batter, focusing on observable indicators such as:

- surface erosion features (e.g. rilling, gullying, sheet wash)
- vegetation establishment and cover density
- signs of instability (e.g. cracking, slumping, toe erosion)
- drainage system integrity and flow concentration issues.

Observations are recorded using a structured inspection template and supported with photographs. Where necessary, corrective actions or additional monitoring recommendations are documented to ensure the ongoing integrity of the trial.

3.1.2 Integration for model calibration

By integrating ground-based inspections with conventional LiDAR and drone surveys, a high-quality dataset is being developed to evaluate batter slope performance over time. These datasets are aligned spatially and temporally, allowing direct comparison of observed erosion patterns with LEM predictions. The outcome is a robust foundation for refining model inputs such as soil erodibility, vegetation cover parameters and run-off thresholds, ultimately improving the predictive capability of LEMs for closure design and PRCP validation.

This integrated monitoring approach ensures that both macro-scale (slope wide) and micro-scale (localised) processes are captured, enhancing understanding of the interactions between batter geometry, material properties and climatic drivers under field conditions.

4 Vegetation performance assessment

Based on drone imagery captured during the site monitoring period, the RGB-based vegetation index (RGBVI) was calculated. RGBVI, derived from visible light spectrum data, serves as a proxy for vegetation cover and can be compared to the normalised difference vegetation index (NDVI). NDVI is a near infrared (NIR)-based index that detects vegetation chlorophyll, which strongly reflects NIR wavelengths. In this study, NDVI values were obtained from Sentinel-2 satellite imagery, which directly captures NIR reflectance. As drone imagery was collected using standard RGB camera and did not include NIR sensor, NDVI could not be calculated directly from the drone data. Accordingly, the Sentinel-2 NDVI dataset was adopted as the reference NDVI dataset against which RGBVI results were compared.

However, due to the spatial resolution limitations of satellite data (typically 30 to 50 m), the derived NDVI may not accurately represent small-scale features such as individual soil capping lots, which are approximately 10 m wide. Therefore, high-resolution drone imagery is essential for assessing vegetation conditions at the lot scale. To make the drone-derived RGBVI more representative, a calibration against the reference NDVI was necessary.

An innovative approach was applied using a machine learning method, random forest regression, to calibrate RGBVI against the remote sensing NDVI. The model achieved a high Pearson correlation coefficient ($r = 0.943$)

and a low root mean square error (RMSE = 0.019), indicating a strong and accurate calibration. As shown in Figure 1, this method effectively handles nonlinear and noisy datasets while automatically capturing feature interactions and higher-order relationships.

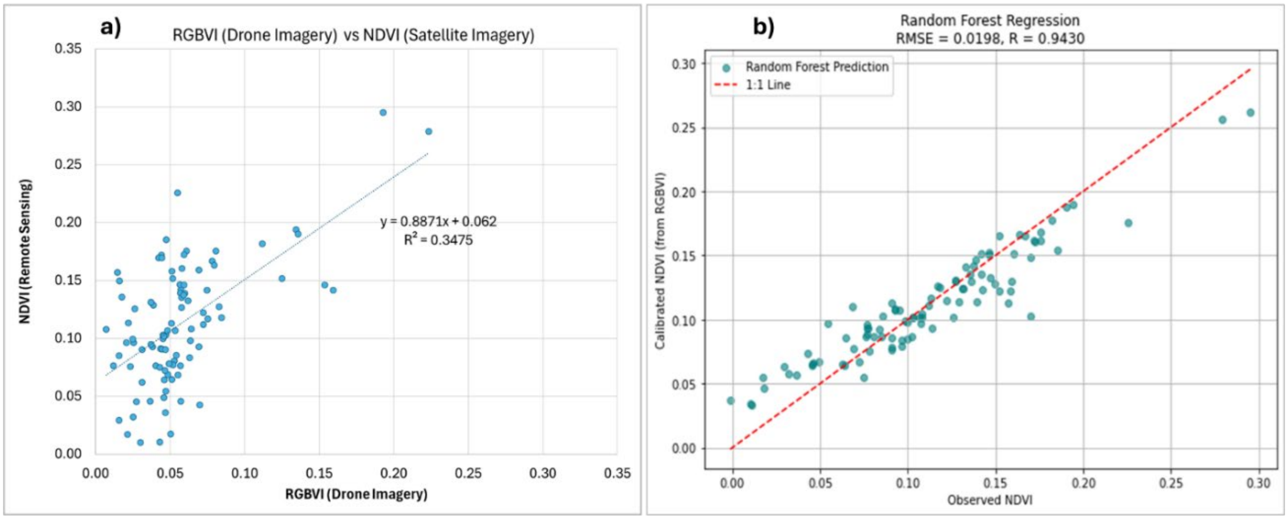


Figure 1 (a) Comparison between uncalibrated RGB-based vegetation index (RGBVI) and normalised difference vegetation index (NDVI); (b) Comparison between calibrated RGBVI and NDVI where Root Mean Squared Error (RMSE) and Correlation coefficient (R) statistic are presented.

The remote sensing NDVI was further extracted and compared with the calibrated RGBVI during the soil capping trial period from 2021 to 2025, as shown in Figure 2. Overall, NDVI shows an increasing trend, reflecting the effectiveness of the implemented vegetation scheme. Additionally, a strong correlation is observed between seasonal conditions, with NDVI increasing during wet seasons and decreasing during dry seasons.

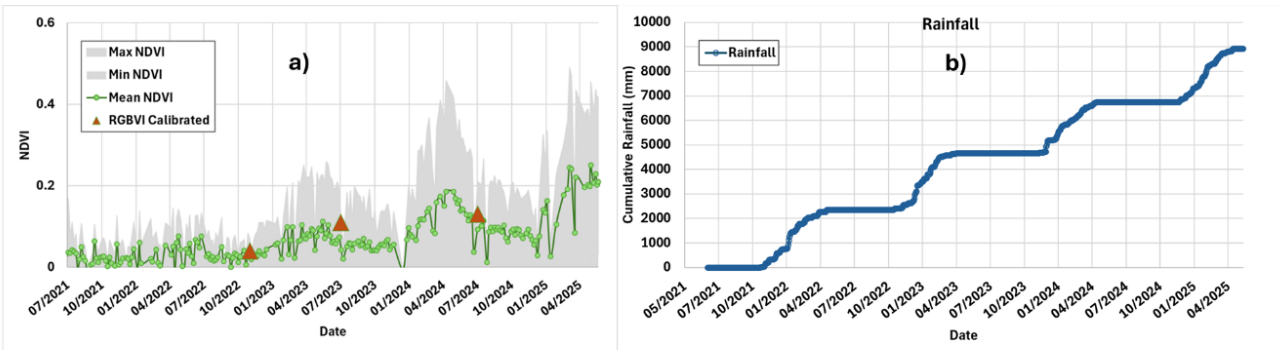


Figure 2 (a) Remote sensing normalised difference vegetation index (NDVI) and calibrated RGB-based vegetation index (RGBVI) during the soil capping trial period from 2021 to 2025; (b) Cumulative rainfall recorded over the same trial period

Further analysis of RGBVI was conducted at the individual lot level. The spatial distribution of the calibrated RGBVI from the 3 drone imagery acquisitions is presented in Figure 3.

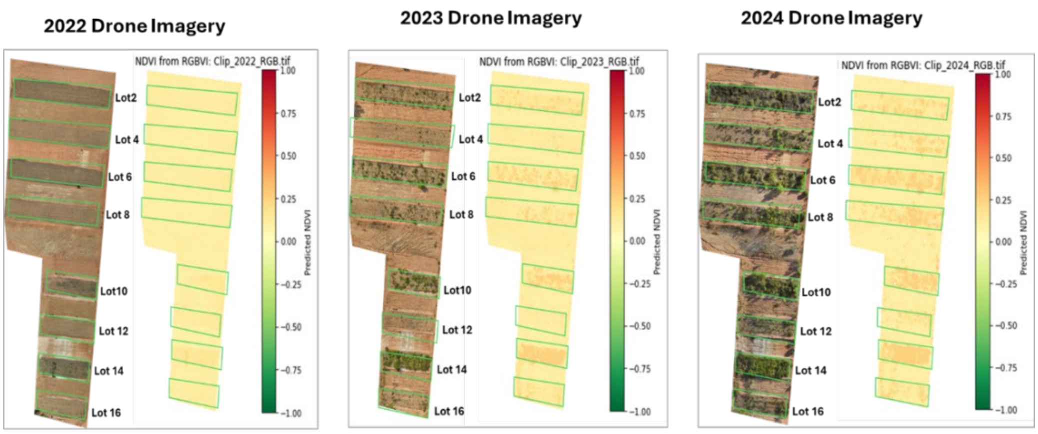


Figure 3 Spatial distribution of calibrated RGB-based vegetation index (RGBVI) derived from the 3 drone imagery and used to estimate normalised difference vegetation index (NDVI)

The vegetation cover ratio was calculated based on the derived RGBVI values, ranging from 0 to 1, where 0 represents bare soil and 1 indicates full (100%) vegetation cover.

5 Trial batter performance assessment

Trial batter performance was assessed through a combination of quantitative erosion rate analysis and qualitative monitoring of visible surface features. Annual erosion rates for each treatment lot were determined by calculating the volumetric difference between 2 high-resolution lidar surveys conducted approximately one year apart following the wet season. This approach provided an accurate measurement of surface change attributable to erosional processes within each defined lot area. A summary of calculated erosion rates for each lot between 2022 and 2024 is detailed in Figure 4.

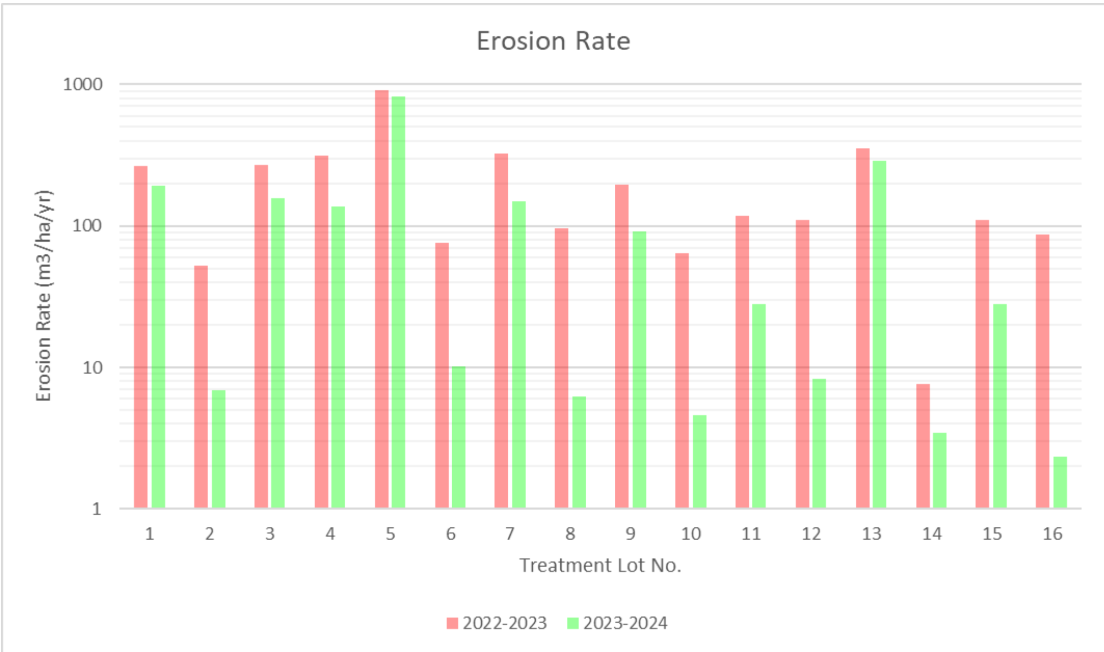


Figure 4 Erosion rate calculation for each trial batter lot

In addition to erosion rate calculations, batter performance monitoring included visual assessment of surface erosion features such as riling, gullying and sheet washing, as well as signs of potential instability such as surface cracking, batter slumping, toe erosion and flow concentration issues. Erosion gullies were monitored in detail using high-resolution drone orthomosaic imagery loaded into QGIS. By generating surface profiles across selected erosion features, the evolution of gully growth could be assessed spatially and temporally, enabling targeted monitoring of critical areas. Findings were then communicated to the site inspection team, who conducted field verification and collected ground truth data for record keeping and evaluation. These results and observations were used to calibrate LEM modelling to reflect site conditions.

The comparative erosion rate results between the 2022 to 2023 and 2023 to 2024 periods in Figure 4 demonstrate a clear trend of improved erosion control associated with vegetation cover establishment. Significant reductions in erosion rates were observed in multiple lots, most notably lots 2, 6, 8, 10, 12, 14 and 16, where erosion declined by more than an order of magnitude. These results correlate with vegetation cover ratios shown in Table 2. The results suggest that vegetative ground cover was effective in stabilising surfaces, reducing run-off energy and controlling sediment displacement. The impact was most evident in areas with initially high erosion, supporting the use of revegetation strategies as a practical and sustainable method for long-term batter stability and erosion management.

Table 2 The vegetation area RGB-based vegetation index cover ratio

Lot	2022 (%)	2023 (%)	2024 (%)
2	5.5	31.5	43.3
4	3.4	11.6	32.4
6	4.8	39.1	76.3
8	2.6	19.9	48.0
10	9.8	50.8	74.3
12	6.8	9.1	31.9
14	18.1	76.6	87.0
16	4.7	21.9	36.0

The relationship between the erosion rate and vegetation cover ratio is illustrated in Figure 5. An exponential decay trend was observed, indicating that erosion rates decrease as vegetation cover increases. This finding aligns with previous studies such as Zuazo & Pleguezuelo (2009), which also reported an exponential relationship between vegetation cover and soil erosion reduction.

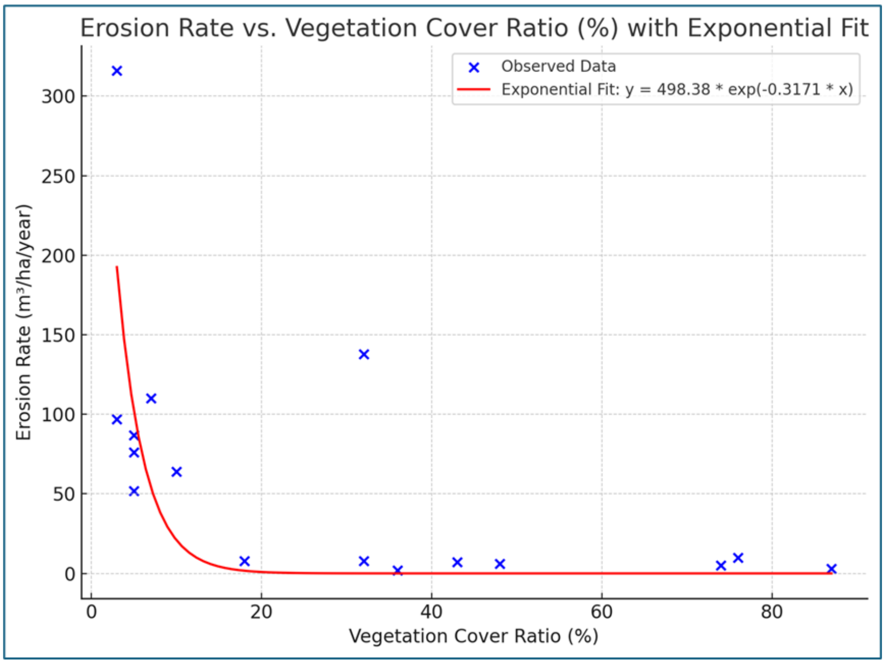


Figure 5 The relationship between erosion rate and vegetation cover ratio

6 SSSPAM model set-up, calibration and results – lot 5

The SSSPAM was applied to simulate erosion and surface evolution for lot 5 (5H:1V batter, ironstone blend, surface treatment A). The DEM for the 2022 lot 5 was used as the initial starting model surface in the SSSPAM. The SSSPAM was configured to represent detachment- and transport-limited erosion processes consistent with the model's formulation for post-construction landforms.

Initial erosion parameters were informed by material-specific characterisation derived from prior flume-based erosion testing of the proposed ironstone blend. These parameters were treated as first-order estimates only and were not assumed to be directly representative of field performance without further calibration.

Model calibration was undertaken by iteratively adjusting the key SSSPAM erosion parameters governing potential fluvial erosion, namely:

- the erodibility parameter (e)
- the discharge exponent (α_1)
- the slope exponent (α_2).

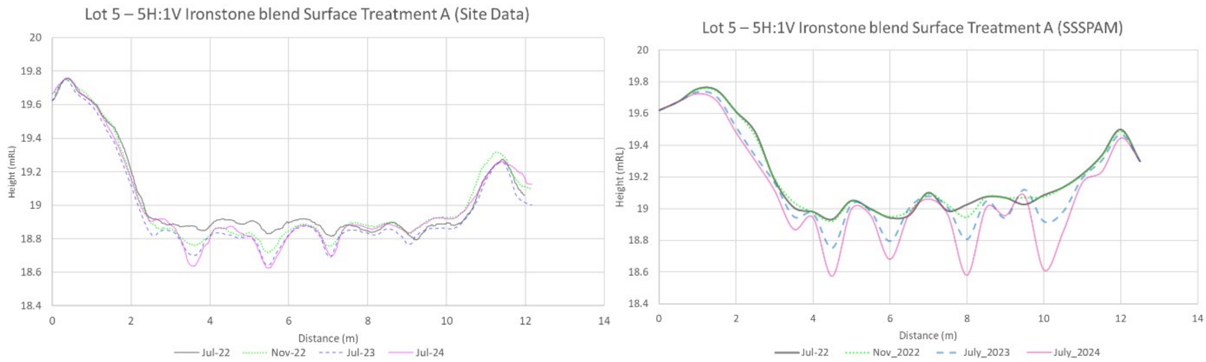
These parameters control the sensitivity of erosion rates to run-off and local slope within the SSSPAM framework.

Simulations were undertaken for durations representative of the monitoring period, and model outputs were compared against independently derived field observations. Field erosion rates were calculated from lidar-derived DEMs for the elevation difference between the periods 2022 to 2024 to estimate erosion loss. Calibration focused on achieving consistency between the LEM and site-observed erosion rates while preserving realistic erosion depths and spatial erosion patterns.

For lot 5, the calibrated SSSPAM simulation produced a mean erosion rate of approximately 790 m^3/ha/year, compared with a field-derived erosion rate of approximately 820 m^3/ha/year. The difference between the modelled and measured erosion rates is considered minor and within the uncertainty associated with lidar surface differencing, spatial variability in erosion processes and survey resolution.

Additional sensitivity testing indicated that further adjustment of erosion parameters to force closer numerical agreement with the measured erosion rate would resulted in increased predicted erosion depths and incision that was inconsistent with observed batter performance. In particular, tighter volumetric calibration led to exaggerated localised erosion features that were not supported by field observations.

Longitudinal cross-sections extracted at the mid-slope of lot 5 demonstrate that the calibrated model reproduces the magnitude and spatial distribution of surface lowering observed in the trial batter. The evolution of surface undulations and localised incision shown in successive lidar-derived profiles is consistent with the erosion behaviour predicted by the SSSPAM. Details of the surface profile comparison between site data and the SSSPAM calibrated model is detailed in Figure 6.



(a) (b)

Figure 6 Surface profile comparison between: (a) Actual site erosion; (b) Calibrated SSSPAM erosion model

Based on the combined assessment of erosion rates, surface morphology and calibration sensitivity, the following erosion parameters were adopted for the lot 5 SSSPAM simulation between 2022 and 2024:

- erodibility parameter (e) = 8
- discharge exponent (α_1) = 1.2
- slope exponent (α_2) = 1.35.

The prediction of the SSSPAM LEM profile in Figure 6 suggests well-calibrated LEMs over the first 3 surveys, but the July 2023 to July 2024 SSSPAM LEM profile shows more severe erosion. Onsite evidence suggests that armouring and vegetation growth in rills may have reduced the erosion rate in the site data profile. Additional site inspections are required to confirm this and adjustment of the calibrated parameter per year may be required to account for these differences noted in the SSSPAM LEM.

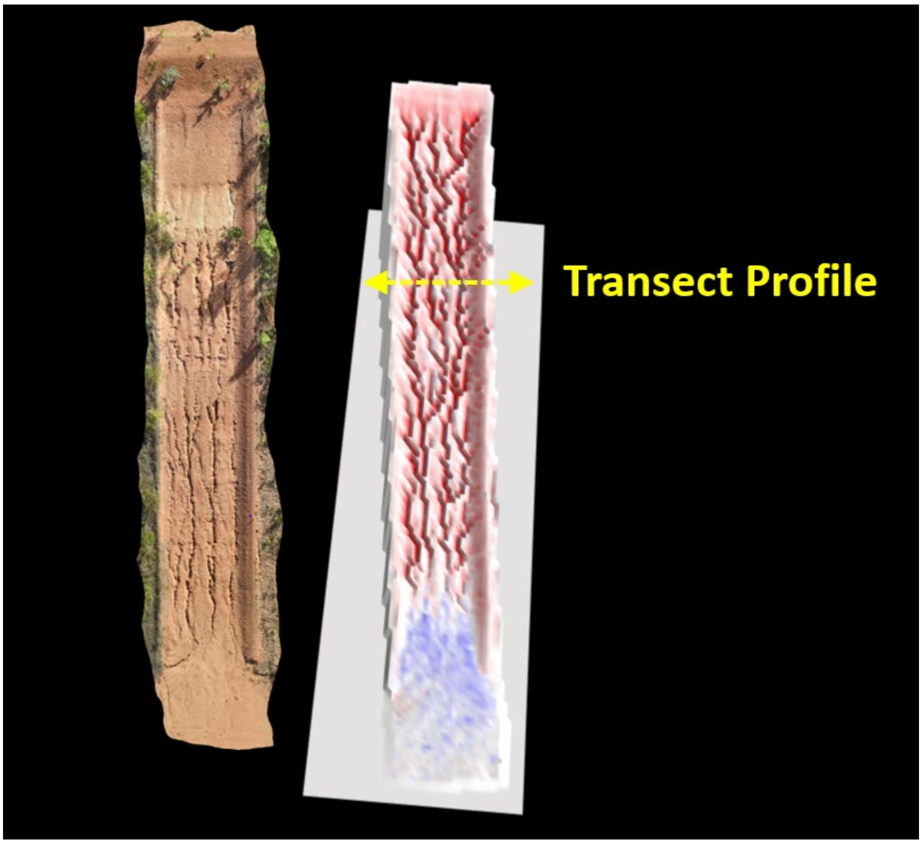


Figure 7 Comparison of drone photos for lots 5 2024 versus the SSSPAM model calibrated between 2022 and 2024

7 Discussion

This study demonstrates the value of full-scale, long-term trial batter studies for improving the calibration and interpretive confidence of LEMs applied to post-mining landforms. By integrating high-resolution remote sensing, UAV drone and survey lidar, site inspections and climatic data, the trial program enabled a nuanced understanding of how batter geometry, surface treatments and vegetation establishment influence erosion processes under tropical conditions.

A key finding is the strong inverse relationship between vegetation cover and erosion rates. Lots that achieved early vegetation strike and progressed to dense vegetation cover exhibited markedly reduced erosion rates over time, often by more than an order of magnitude compared with their initial performance. This trend is consistent with the exponential decay relationship observed between the erosion rate and vegetation cover ratio (Figure 5) and reflects the role of vegetation in increasing surface roughness, dissipating run-off energy and promoting sediment retention. Once established, dense vegetation effectively transitions the system from an erosion-dominated to a transport-limited or diffusion-dominated regime.

However, the study also highlights important limitations associated with erosion monitoring in densely vegetated environments. As vegetation cover increases, lidar-derived DEMs become progressively less reliable for detecting subtle surface changes due to canopy obstruction and reduced ground return density. This limitation reinforces the need for complementary monitoring approaches, including periodic site inspections and targeted drone photography, to identify active erosion features that may no longer be discernible in lidar data alone.

In this context, the use of erosion basins or sediment traps located downslope of trial batter lots is identified as an important monitoring tool for long-term performance assessment. Where vegetation limits direct measurement of surface change, erosion basins provide an indirect but reliable indicator of ongoing sediment mobilisation and allow erosion rates to continue to be quantified even after dense vegetation establishment.

Incorporating such features into trial batter designs improves the robustness of long-term monitoring programs and enhances confidence in erosion rate estimates beyond the early rehabilitation period.

It is also recognised that the surface change derived from successive lidar and UAV-based DEMs does not explicitly differentiate between material loss due to erosion and surface elevation changes associated with settlement or consolidation. For the purposes of this study, settlement is assumed to be minimal relative to the magnitude of observed erosion and is therefore not explicitly accounted for in the analysis.

However, in closure scenarios where ongoing settlement or consolidation of tailings or cover materials is expected to be significant, additional monitoring methods should be considered to distinguish between settlement and erosion processes. These may include survey-based settlement monitoring points, settlement plates, or instrumentation such as shape accel arrays or similar subsurface deformation monitoring systems. Integration of such techniques would support improved quantification of erosion processes and enhance confidence in the calibration of LEMs.

Furthermore, future work could explore the incorporation of settlement-related processes into LEM frameworks such as SSSPAMs. Explicit consideration of settlement and consolidation behaviour within the model framework may further improve the ability to differentiate between deformation-driven and erosion-driven surface change, particularly for tailings facilities where post-construction settlement may be ongoing during early closure phases.

The performance of revegetation treatments also indicates that native site-derived mulch plays a critical role as an erosion mitigation measure and promotes vegetation establishment and growth. Field observations show that mulch persists for extended periods under site conditions, resisting rapid decomposition and providing immediate surface protection during the critical establishment phase. Furthermore, the authors understand that mulch is key to promoting the soil microbiome, which aids in vegetation success. In addition to reducing erosion, the mulch layer appears to function as a medium for retaining moisture, trapping fine material and supporting vegetation establishment through interaction with applied topsoil. These characteristics suggest that native site mulch represents a key control strategy that is well suited to tropical mine closure applications.

Importantly, calibration of the SSSPAM model was intentionally focused on trial lots exhibiting poor vegetation establishment and sustained measurable erosion. These conditions provide the most reliable dataset for parameter calibration because erosion processes are active, spatially observable and quantifiable using lidar, UAV surveys and field inspections. As such, the calibrated parameters presented in this study should be interpreted as representative of early stage or poorly vegetated closure conditions, with vegetation effects incorporated implicitly through reduced erosion activity rather than explicit parameter adjustment. Having said that, the actual erosion rates and depths can be used to estimate erosion of well-established vegetated lots where concentrated flow paths are presented

Finally, it is recognised that the dataset presented represents an early stage in the life cycle of the rehabilitated landform. Continued monitoring over longer periods will enable progressive refinement of LEM parameters, improved representation of vegetation erosion and increased confidence in long-term landform evolution predictions. As additional lidar surveys, vegetation data and sediment yield records become available, the modelling framework established in this study can be iteratively updated, reducing uncertainty and strengthening its application to final relinquishment assessments.

8 Conclusion

This paper presents a comprehensive framework for establishing and utilising full-scale trial batter studies to calibrate landform evolution models for post-mining landform relinquishment. By combining high-resolution lidar, UAV imagery, vegetation analysis and structured site inspections, the study provides a robust empirical basis for assessing erosion performance and informing model parameterisation under tropical climatic conditions.

The results demonstrate that vegetation establishment is a dominant control on erosion rates, with early vegetation strike and dense cover leading to substantial reductions in surface erosion. Native site-derived mulch was identified as a particularly effective erosion mitigation measure, providing both immediate surface protection and a favourable medium for vegetation establishment. At the same time, the study highlights important monitoring limitations once dense vegetation is established, emphasising the continued role of site inspections and erosion basins in long-term performance evaluation.

Calibration of the SSSPAM model using trial lots with sustained observable erosion enabled defensible parameter selection and realistic reproduction of erosion patterns and magnitudes. While the model results demonstrate good agreement with field observations at this stage, the authors emphasise that ongoing data collection will be essential to further refine calibration and strengthen long-term predictions of landform evolution.

Overall, the integrated trial monitoring modelling approach presented in this paper provides a practical and transferable methodology for mine closure practitioners, regulators and researchers. By grounding predictive models in site-specific empirical data, this framework supports the development of resilient, low-maintenance landforms and improves confidence in achieving successful post-mining landform relinquishment.

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