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Assessing the influence of variable batter gradients on long-term erosional stability of rehabilitated mine landforms: application of MINErosion 3 as a design tool

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Abstract

Mine closure projects frequently require verification that reconstructed landforms will achieve long-term erosional stability under defined slope constraints and cover-system configurations. A recurrent engineering and regulatory question concern the implications of modifying batter gradients (e.g. from 16.7% to 20% or 25%) on both erosional response and hydrological performance, particularly where alternative cover materials and depths are proposed.

This paper reviews modelling approaches available for assessing slope-gradient sensitivity in post-mining landscapes, including RUSLE, WEPP and Landscape Evolution Models (LEMs), and identifies their respective strengths and limitations for design optimisation. The MINErosion 3 hillslope erosion model is then presented as a practical and scientifically validated tool for assessing the effect of slope gradient, slope length and vegetation cover on both annual and event-based erosion rates. Drawing upon the original development and validation documented in Khalifa (2010) and So et al. (2018), this paper demonstrates how MINErosion 3 can be utilised iteratively as a design-support tool to evaluate alternative batter geometries and cover systems, thereby informing Environmental Authority amendments and Progressive Rehabilitation and Closure Plan (PRCP) updates.

Keywords: *soil erosion, modelling, WEPP, MINErosion, rehabilitation, open cut, mining*

1 Introduction

Open cut mining fundamentally alters landscape morphology, often generating elevated spoil or reject landforms requiring reshaping and stabilisation to achieve an approved post-mining land use. Long-term erosional stability is a central performance criterion, as uncontrolled rill and gully development can compromise encapsulation integrity, reduce ecological function and increase offsite sediment delivery (Department of Environment and Science 2023).

The need to "reshape and lower the slopes to allow the development of sustainable ecosystems" is well established in post-mining rehabilitation research. Regulatory frameworks typically impose maximum slope constraints (for example, 1V:6H equivalent to 16.7%), yet operational and volumetric considerations often motivate assessment of steeper alternatives such as 20% or 25% grades.

The technical challenge is therefore to determine, quantitatively and defensibly, how incremental increases in slope gradient influence:

- mean annual soil loss
- storm event erosion risk

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- sensitivity to vegetation establishment and consolidation
- the performance of alternative cover materials with differing erodibility characteristics.

Such assessment must be grounded in validated modelling tools capable of representing rill and inter-rill processes at hillslope scale and, where required, extended to catchment-scale using LEMs.

2 Modelling approaches for slope-gradient sensitivity assessment

2.1 RUSLE and WEPP

The Revised Universal Soil Loss Equation (Renard 1997) and the Water Erosion Prediction Project (Flanagan et al. 2007) are widely used soil erosion models in mine rehabilitation studies.

However, both are primarily erosion prediction tools rather than geomorphic evolution models. As summarised in the technical review on applying erosion and landscape evolution models, RUSLE and WEPP do not simulate landform evolution; they estimate erosion rates under specified parameterisations. RUSLE provides a practical empirical framework for estimating long-term average sheet-and-rill erosion, but a recognised limitation is that it is less reliable where runoff becomes concentrated or overland flow behaviour departs from the simplified assumptions embedded in the LS factor.

WEPP provides process-based simulation of infiltration, runoff and sediment transport but requires daily climate inputs (typically ≥100 years) and detailed parameterisation, making it relatively complex for rapid design iteration. While highly valuable for detailed assessment, WEPP can also be used relatively efficiently to assess slope geometry sensitivity by adjusting the slope profile input; however, it still requires calibrated parameters and more detailed parameterisation than is typically needed for rapid preliminary design screening across multiple scenarios.

2.2 Landscape Evolution Models (SIBERIA, CAESAR-Lisflood)

Landscape Evolution Models (LEMs) such as SIBERIA (Willgoose et al. 1991) operate on a DEM grid, calculating erosion and deposition at each cell and allowing the landform to evolve through time. They are particularly suited for assessing long-term gully development and spatial patterns of instability, including catchment-scale integration.

LEMs can identify the likely location and intensity of gullying under different slope configurations and are considered best practice for whole-of-landscape assessment. However, they require suitably detailed DEMs and careful calibration of hydrology and sediment transport parameters. Their complexity may limit their utility during early-stage geometric optimisation where numerous slope-gradient scenarios must be rapidly evaluated.

3 Development and validation of MINErosion 3

MINErosion 3 (Khalifa 2010; So et al. 2018) was developed as a steady-state hillslope erosion model specifically for steep post-mining landscapes. It evolved from MINErosion 2 (Sheridan et al. 2000) and incorporates a runoff generator and algorithms representing vegetation cover and soil consolidation effects. The model links laboratory-derived rill and inter-rill erodibility parameters with RUSLE (for mean annual erosion) and MUSLE (for event-based erosion). A key objective was to derive “the key design criteria of slope length, slope gradient and vegetation cover that would lead to acceptable erosion rates”. Validation against field plots on rehabilitated post-mining landscapes demonstrated strong agreement between predicted and measured erosion rates. For annual soil loss, regression analysis yielded a relationship close to the 1:1 line (R^2 = 0.86; Nash–Sutcliffe efficiency = 0.755). Event-based validation similarly showed robust predictive capability across soil and overburden plots.

The model includes an embedded database of soil and overburden erodibility parameters from Central Queensland mines and allows estimation from routinely measured soil properties where direct flume measurements are unavailable.

Importantly, MINErosion 3 was explicitly designed as a user-friendly application enabling mine sites to estimate mean annual and storm-event erosion rates from proposed landform configurations.

4 Application to variable batter gradients and alternative cover systems

4.1 Influence of batter gradient and slope geometry on erosion response

MINErosion 3.4 provides a practical framework for assessing how variations in batter gradient and slope geometry influence erosion risk on rehabilitated mine landforms. Incremental increases in batter gradient, for example from 16.7% to 20% and 25%, are expected to produce a non-linear increase in predicted erosion. Steeper slopes increase the influence of slope length and slope steepness within annual erosion calculations and also intensify the hydraulic conditions that promote rill detachment and sediment transport during runoff events. As slope increases, flow velocity, shear stress, and transport capacity also increase, while the time required to generate effective runoff is reduced. The result is a more erosion-prone hillslope, particularly where the surface is long, uninterrupted, and lacks effective protection. This interpretation is consistent with the development of MINErosion 3, which showed that rill erosion becomes increasingly important as slope length increases, whereas interrill erosion is comparatively less sensitive to slope length.

The practical implications of this behaviour are especially important for outer batters on constructed mine landforms. In these settings, slope angle cannot be considered independently of slope length, because a modest increase in gradient may have limited effect on a short batter but may result in a substantial increase in erosion on a longer uninterrupted slope. Accordingly, assessment of batter-gradient sensitivity should explicitly consider the interaction between gradient and slope length, rather than treating either factor in isolation. MINErosion 3.4 is suited to this task because it provides both numerical predictions and graphical outputs showing how erosion changes across a range of slope lengths for a nominated slope gradient and surface condition.

The effect of slope geometry is most critical during the early stages of rehabilitation. Freshly placed batter materials are commonly loose, unconsolidated, and only sparsely vegetated. Under these conditions, steeper slopes are more susceptible to runoff concentration, rill incision, and elevated sediment export. Published simulations associated with the MINErosion framework demonstrated that bare and non-consolidated conditions can yield event-based erosion rates orders of magnitude higher than those predicted for consolidated and vegetated surfaces. This reinforces the need to assess batter steepness in conjunction with the likely progression of consolidation and vegetation establishment over time.

4.2 Assessment of alternative cover materials and surface conditions

These three approaches are not equivalent in confidence. Directly measured rill and interrill erodibility provides the strongest site-specific basis for application, the embedded database provides a strong analogue-based option where comparable mine materials are represented, and the pedotransfer-based approach is useful where only limited laboratory data are available. Even where direct erodibility measurements are available, MINErosion 3.4 remains useful as a rapid and user-friendly hillslope design tool, whereas WEPP generally requires additional effort to assemble and calibrate climate, slope, soil, and management inputs for comparative scenario testing.

This operational structure makes the model particularly suitable for comparative testing of candidate cover materials, such as sandstone-derived media, tertiary-derived spoil, topsoil substitutes, or other engineered growth media. Materials can be compared under identical slope and rainfall conditions by substituting their respective erodibility parameters and then assessing their response at different batter gradients and slope lengths. Thus, Material A can be tested at 16.7%, 20%, and 25%, and directly compared with Material B at the same gradients and slope lengths. This approach provides a transparent basis for quantifying whether a more erosion-resistant material can offset the increased erosion risk associated with a steeper batter, or whether a given material is only suitable under more conservative slope geometries.

MINErosion 3.4 also supports comparison of contrasting surface conditions representing the rehabilitation trajectory. After erodibility has been assigned, the model calculates the erodibility terms required for storm-based and annual prediction under both bare and consolidated conditions and allows the user to assess either a single storm event or long-term annual erosion. In practice, this means that each material can be tested not only as a freshly placed, bare, and unconsolidated surface, but also as a consolidated surface and under varying levels of vegetation cover. This is a substantial advantage for mine rehabilitation assessment, because the highest erosion risk commonly occurs in the early post-construction period before the batter has consolidated and before vegetation cover has become effective. The model therefore enables direct comparison between early-year exposure and the longer-term stabilised condition.

Vegetation cover is incorporated explicitly within this comparative framework. The program presents outputs not only for bare soil but also for surfaces under different user-specified vegetation-cover levels. This allows the modeller to test whether a proposed batter geometry remains acceptable only under favourable revegetation outcomes, or whether it remains acceptable at lower vegetation cover. Accordingly, MINErosion 3.4 allows material properties, surface condition, and revegetation assumptions to be evaluated as an integrated design system rather than as separate and disconnected considerations.

4.3 Use of MINErosion 3.4 as a comparative design tool

The combined sensitivity of erosion to slope geometry, material erodibility, vegetation cover, and consolidation status makes MINErosion 3.4 particularly valuable as a comparative design tool. Once interrill and rill erodibility have been defined, the user need only specify the rainfall event characteristics, slope gradient, and slope length for the model to predict interrill and rill erosion associated with that storm (Figure 1). The program then provides both numerical outputs and graphical outputs illustrating the relationship between slope length, slope gradient, and erosion rate. This functionality is especially useful during landform design optimisation, because it allows the modeller to move beyond a single-point prediction and assess how erosion response changes systematically as batter geometry is varied.

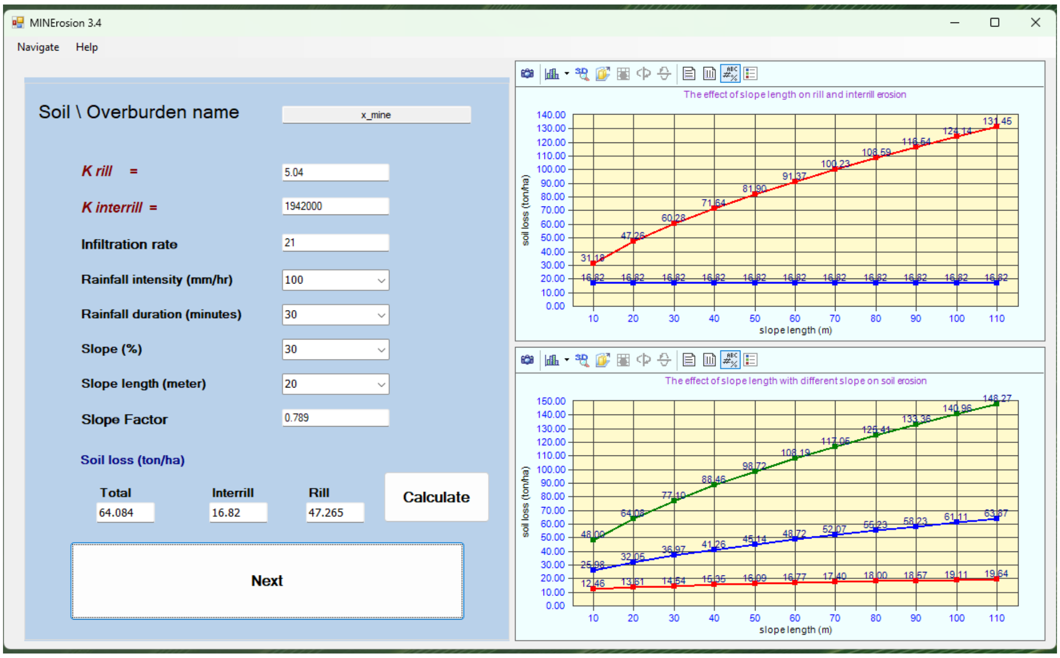

Figure 1 MINErosion 3.4: estimation of rill and interrill soil loss (t/ha), showing the effects of slope length and gradient using the model's graphical interface

In practical terms, this means that candidate designs such as 16.7%, 20%, and 25% batters can be tested iteratively under common climatic conditions and identical slope-length ranges. The model outputs enable direct comparison of whether a steeper batter produces only a moderate increase in erosion, or whether it triggers a disproportionate increase once a critical slope length is exceeded. Because the program presents results graphically over slope lengths ranging from 10 to 130 m (Figure 2), it is particularly well suited to identifying these changes in erosion sensitivity across the tested slope-length range and to determining whether a steeper slope could be made acceptable by reducing uninterrupted slope length, improving surface material properties, or increasing expected vegetation cover. While the annual mode is linked to a RUSLE-style framework, the slope-length response in MINErosion 3 is informed by MINErosion 2, which was developed specifically to address scaling across hillslope lengths by separating rill and interrill erosion processes. In this way, the model does not rely solely on the generic LS factor to represent slope-length effects, although the annual outputs should still be interpreted in a comparative design-support context (Figure 5).

An additional strength of the software is that it supports both annual erosion assessment and single-storm assessment. After calculating MUSLE erodibility values for bare and consolidated soil, the program allows the user to choose between estimating mean annual erosion or erosion associated with an individual storm event (Figure 3). The annual outputs provide the basis for evaluating long-term chronic soil loss and general erosional stability, whereas the storm-event outputs are particularly valuable for examining short-term episodic risk associated with intense rainfall, especially during the vulnerable early stages of rehabilitation. This event-based capability is also important because it helps address a recognised limitation of annual RUSLE-type approaches, which are less suited to representing erosion risk associated with individual high-intensity runoff events. This dual capability is highly relevant for post-mining landforms, where acceptable performance must usually be demonstrated both in terms of long-term average erosion and in terms of resilience to high-intensity events that may threaten cover-system integrity or expose underlying problematic materials.

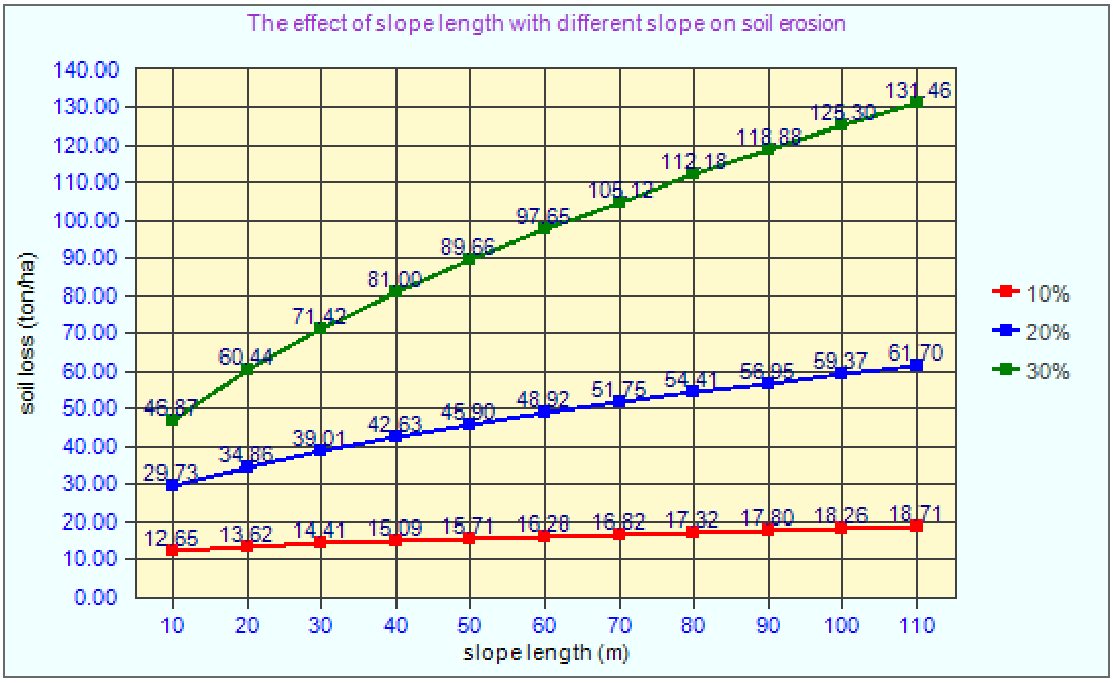

Figure 2 **MINErosion 3.4 outputs: the effect of slope length on soil loss (t/ha) under different slope gradient (bare unconsolidated soil)**

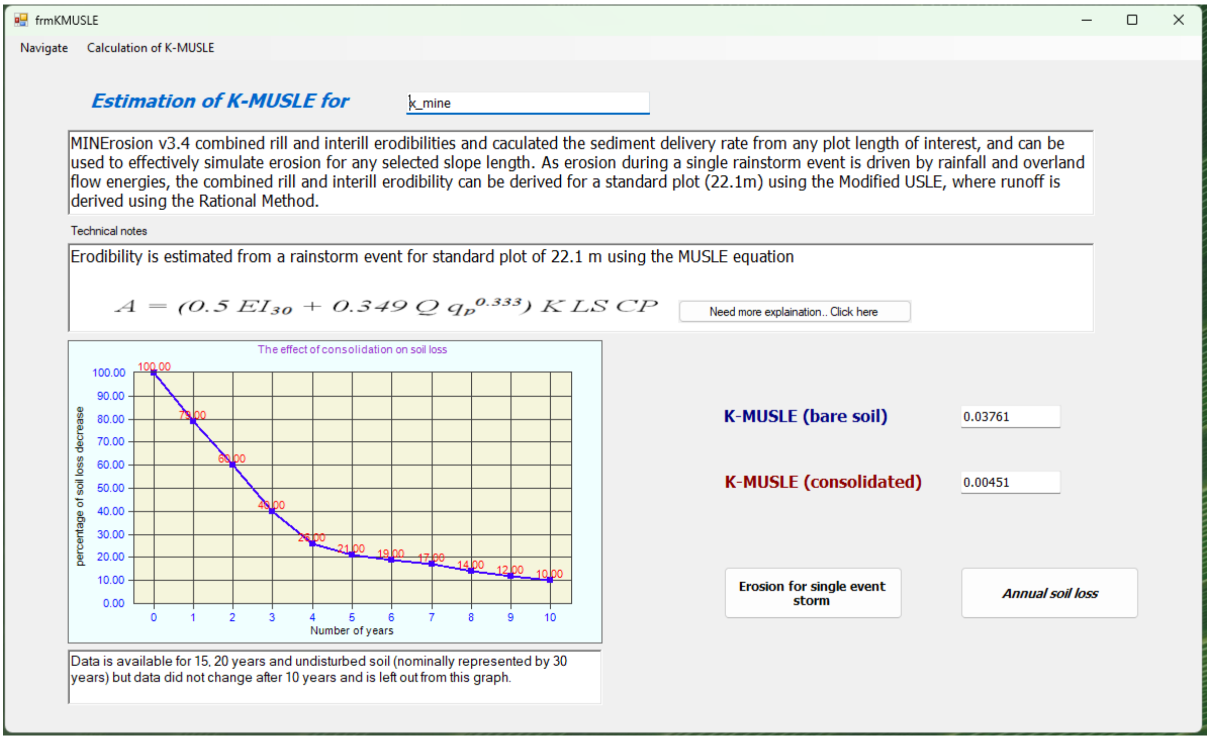

Figure 3 Calculation of K-MUSLE using MINErosion 3.4

Accordingly, MINErosion 3.4 is best viewed as a hillslope-scale comparative design and optimisation tool. Its principal value lies in allowing rapid, transparent, and scientifically defensible comparison of alternative batter gradients and cover-system configurations before more complex catchment-scale or landscape evolution modelling is undertaken. In this role, it helps identify combinations of batter gradient, slope length, material type, and vegetation cover that are likely to provide an acceptable balance between constructability, rehabilitation cost, and long-term erosional stability (Figure 4).

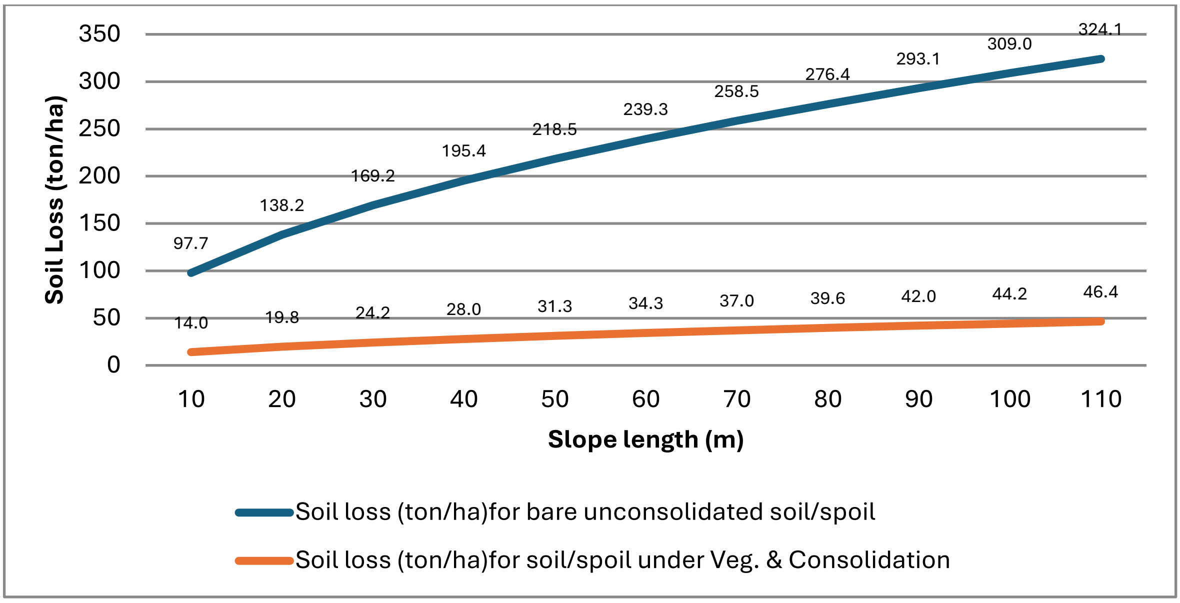

Figure 4 MINErosion 3.4 outputs: a comparison between soil/spoil loss from bare soil and soil loss under 50% veg. cover of Tussocky grass and 3 years of consolidation

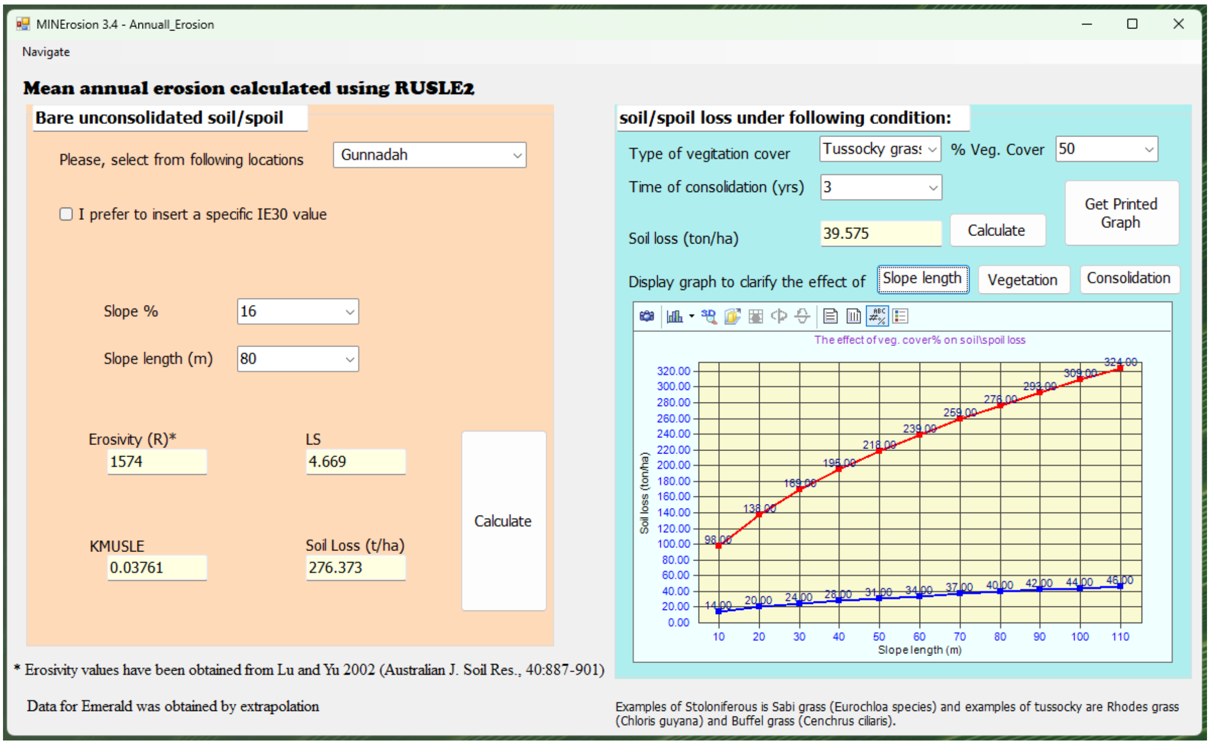

Figure 5 MINErosion 3.4 outputs

5 Integration with broader landform design strategy

5.1 Scenario definition and model inputs

To assess the influence of variable batter gradients on erosional stability, MINErosion 3.4 should be applied through a structured scenario-based framework in which slope geometry, material properties, and surface condition are varied systematically while climatic inputs are held constant within each modelling set. The purpose of this framework is not simply to estimate erosion for one nominated hillslope, but to establish the relative sensitivity of erosion to plausible design alternatives. This is particularly important in post-mining rehabilitation, where decisions regarding batter gradient are closely linked to cover material selection, slope length, revegetation expectations, and the likely timing of consolidation. The published MINErosion 3.4 model was developed specifically to derive suitable combinations of slope gradient, slope length, and vegetation cover that would result in acceptable erosion rates on rehabilitated mine slopes.

The first step in the modelling framework is to define the principal design scenarios. These should include the batter gradients under consideration, such as 16.7%, 20%, and 25%, together with an appropriate range of slope lengths representative of the proposed landform geometry. Because erosion response is strongly dependent on material properties, each batter-gradient case should be tested for each candidate cover material or outer batter material likely to be used in final construction. MINErosion 3.4 allows this to be done by selecting materials from its embedded database, estimating erodibility from measured soil or spoil properties using internal pedotransfer functions, or inputting directly measured rill and interrill erodibility values obtained from rainfall-simulator and flume experiments. This enables both preliminary screening based on available laboratory data and more detailed assessment where site-specific erosion testing has been undertaken. In this context, preliminary screening refers to early comparison of alternative batter gradients, slope lengths, cover materials, and assumed vegetation or consolidation states using available laboratory soil or spoil data before direct erosion testing has been completed.

The second component of scenario definition is the specification of surface condition. For each combination of batter gradient, slope length, and material type, simulations should be undertaken for contrasting rehabilitation states. At minimum, these should include a bare and non-consolidated condition representing the immediate post-construction phase, a bare but consolidated condition representing increased surface resistance after settlement, and one or more vegetated conditions representing progressive establishment of protective ground cover. Such differentiation is necessary because the MINErosion framework explicitly incorporates both consolidation and vegetation-cover effects, and previous work has shown that these factors can substantially reduce predicted erosion relative to freshly placed bare surfaces.

5.2 Annual and event-based modelling strategy

The modelling framework should include two complementary modes of assessment: mean annual erosion simulation and single-storm erosion simulation. Mean annual erosion-modelling provides an estimate of long-term average soil loss and is therefore appropriate for assessing whether a proposed batter configuration is likely to satisfy general erosional stability objectives over time. In contrast, single-storm modelling is used to examine the response of the same hillslope configurations to rainfall events of specified intensity and duration, thereby identifying short-term vulnerability to episodic erosion during extreme or high-intensity storms. This dual approach is consistent with the architecture of MINErosion 3.4, in which annual erosion prediction is linked to a RUSLE-based framework and event erosion prediction is linked to MUSLE-based calculations. In MINErosion 3.4, the difference between the annual and event modes lies in the erosivity term used rather than in applying the same rainfall erosivity value to both. Event erosion is estimated using storm-specific EI30 derived from the nominated rainfall intensity and duration, whereas annual erosion is estimated using mean annual EI30 based on the long-term rainfall pattern for the selected location.

The mean annual simulations should be used to compare the chronic erosion implications of alternative batter gradients and cover-system configurations. These outputs are especially useful for identifying whether increases in slope steepness cause unacceptable long-term increases in soil loss, and whether such increases can be offset by selection of less erodible materials, shorter slope lengths, or greater vegetation cover. The event-based simulations, by contrast, should be used to test risk during the early years of rehabilitation, when vegetation cover may still be sparse and the surface may not yet be fully consolidated. In practical terms, the event-based outputs provide an important check on whether a design that appears acceptable in annual terms may still be vulnerable to unacceptable erosion during severe rainfall events.

For each scenario, MINErosion 3.4 provides both numerical and graphical outputs. The numerical results give the predicted erosion rate for the nominated hillslope configuration, whereas the graphical outputs illustrate erosion response across a range of slope lengths for the selected gradient and surface condition. These response curves are especially valuable because they reveal whether the effect of increasing batter gradient remains moderate across the full slope-length range or whether it becomes disproportionately large beyond a certain slope length. This allows the modeller to identify threshold-type behaviour in which the interaction between slope gradient and slope length becomes critical to design performance.

5.3 Interpretation of outputs for design optimisation

The final stage in the framework is interpretation of the modelling outputs in terms of practical landform design decisions. The objective is to determine not only whether a given batter gradient is acceptable, but under what conditions it remains acceptable. A steeper batter may perform satisfactorily where slope length is limited, a relatively erosion-resistant cover material is used, and reliable vegetation establishment can be achieved. However, the same gradient may become unacceptable where the slope is long, the material is highly erodible, or the surface is likely to remain bare and unconsolidated for an extended period. The framework therefore enables slope design, material selection, and revegetation assumptions to be evaluated as an integrated design problem rather than as separate considerations.

In practical terms, MINErosion 3.4 may be viewed as a mine-specific hillslope design tool that combines the MINErosion rill/interrill erodibility framework with RUSLE- and MUSLE-linked annual and event prediction modes. Its value lies primarily in comparative assessment of alternative design scenarios rather than in representing all erosion processes in a fully process-based way.

This is especially important where alternative designs involve trade-offs between earthworks efficiency and rehabilitation risk. For example, increasing batter steepness may reduce reshaping costs or improve spoil storage efficiency, but the modelling may show that this benefit is offset by substantially higher early-stage erosion risk or by greater dependence on successful vegetation establishment. Conversely, the modelling may indicate that a moderate increase in batter gradient remains acceptable if accompanied by a reduction in uninterrupted slope length or by substitution of a more erosion-resistant outer cover material. In this respect, MINErosion 3.4 functions as a comparative optimisation tool rather than simply a predictive model.

The reliability of the predicted outcomes depends on the quality and type of erodibility input used. Directly measured rill and interrill erodibility provides the strongest site-specific basis for assessment, while pedotransfer-estimated values and database-selected analogue materials are more suitable for preliminary screening. Although published validation against field erosion plots showed generally good agreement between predicted and measured annual and event erosion rates, the model should still be applied with appropriate caution across different soil and spoil types, particularly where site-specific calibration data are limited.

Accordingly, the proposed modelling framework should be viewed as a hillslope-scale optimisation stage within a broader landform assessment process. MINErosion 3.4 is well suited to rapid and transparent comparison of batter-gradient scenarios and alternative cover systems, but it remains a hillslope model and does not replace the need for larger-scale assessment where sediment delivery pathways, drainage organisation, and gully development must also be considered. Its principal value lies in identifying batter geometries and cover configurations that are likely to be defensible from an erosional stability perspective before more complex catchment-scale or landscape evolution modelling is undertaken. In that role, it provides a scientifically grounded and practically useful basis for selecting batter designs that balance constructability, rehabilitation cost, and long-term stability.

6 Conclusion

Changes in batter gradient from 16.7% to 20% or 25% can materially influence the long-term erosional behaviour of rehabilitated mine landforms. The response is not linear and cannot be attributed to slope angle alone. Rather, predicted erosion is governed by the combined effects of batter gradient, slope length, material erodibility, vegetation cover, and surface consolidation. For this reason, evaluation of steeper batter options must be undertaken within an integrated design framework that considers both landform geometry and cover-system performance through time.

Within the available suite of erosion-modelling tools, MINErosion 3.4 fills an important intermediate role. Empirical and process-based models such as RUSLE and WEPP provide valuable erosion prediction capability, while landscape evolution models such as SIBERIA are required to assess longer-term geomorphic adjustment, drainage development, and spatial patterns of instability. MINErosion 3.4, however, provides a scientifically validated, user-friendly, hillslope-scale design tool that is particularly well suited to rapid comparison of alternative batter geometries, cover materials, and rehabilitation states. Its development and validation against laboratory and field data support its application as a defensible tool for comparative assessment of rehabilitated mine slopes.

Applied iteratively, MINErosion 3.4 offers a transparent basis for quantifying batter-gradient sensitivity, testing alternative cover materials, evaluating early-stage erosion risk, and informing design decisions relevant to closure planning and regulatory approval. Nevertheless, its scope remains that of a hillslope model. It does not simulate whole-catchment evolution, sediment connectivity, or gully-network development, and therefore should not be used in isolation where whole-of-landform stability must be demonstrated.

A tiered modelling framework is therefore recommended. In the first stage, MINErosion 3.4 should be used to optimise hillslope design by identifying acceptable combinations of gradient, slope length, material type, and surface condition. In the second stage, the preferred hillslope configurations should be verified at catchment or landform scale using MINErosion 4, WEPP, or landscape evolution models such as SIBERIA to confirm that the final design does not introduce unacceptable gullying, sediment connectivity, or offsite sediment impacts. This staged approach is consistent with recent technical guidance advocating iterative use of predictive models throughout the landform design process.

Overall, MINErosion 3.4 should be regarded as a practical and scientifically robust design-support tool for assessing the erosional implications of alternative batter-gradient configurations at the hillslope scale. When embedded within a broader multi-scale modelling framework, it provides a strong basis for improving the transparency, defensibility, and technical quality of post-mining landform design. Future work should focus on tighter integration between hillslope-scale optimisation and DEM-based landform evolution modelling so that local batter design decisions can be linked more explicitly to whole-of-landform stability over decadal to centennial timescales.

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