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A new way to geoengineer landscapes using computer-based landform evolution models

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Abstract

The design and construction of post-mining landforms is a complex undertaking where any structure requires integration with underlying materials and the surrounding unmined or undisturbed landscape. A common reconstruction design for post-mining landscapes is to have linear hillslopes with drains or runoff diversion structures that are designed for the hillslope length, angle and climate. These landscapes are easy to construct and result in a surface which can be easily traversed by agricultural machinery, while the benches often rely on drainage control structures to manage runoff and resultant erosion. Few mines worldwide have committed to a catchment-based reconstruction approach or that employing geomorphic design. Here, a method for catchment design has employed a simple strategy of an uplifted catchment being allowed to evolve using a computer-based Landscape Evolution Model until the volume matches that of a proposed design. The computer-generated landforms are compared with that of a catchment created using site hydrology and sediment transport conditions (Expert Knowledge) by a recognised design engineer. The results demonstrate that a computer-generated landscape produces sediment output within that of target erosion rates with low gully depths. The design created using Expert Knowledge produces sediment output above background erosion rates as well as having maximum gully depths of up to 2.7 m. Modelling demonstrates that computer-generated designs produce erosion rates which are approximately one-third to half that of the Expert Knowledge design, with a commensurate reduction in maximum gully depth. The computer model-generated catchments also have a more natural appearance with regular curvature and channel definition. A key finding is that landscapes with a series of smaller catchments and a more complex drainage network produce less sediment output.

KEYWORDS
GeoFluv, geomorphic design, Landscape Evolution Model, mine rehabilitation, SIBERIA

1 | INTRODUCTION

Humans disturb the earth's surface in pursuit of raw materials to enhance living standards, provide social benefit and to support a growing global population and resultant economy. Open cut mining, that is, mining which removes the earth's surface to access the mineral of interest, exhumes huge volumes of earth globally and has the potential to create entirely new landscapes and ecosystems (Hancock et al., 2019; Mossa & James, 2022).

Post-mining, the excavation and exhumed material is required to be reconstructed so that the new landscape is 'safe, stable and non-polluting'. Post-mining, the landscape must be ecologically self-sustaining and integrate with the surrounding non-mined landscape according to an agreed post-mining land use (Supervising

Scientist, 2021; Zapico et al., 2018). The new landform will then become part of the surrounding landscape arrangement and evolve as part of that system over geological time. That is, the new landscape will be present for geological time.

It should be noted that all landscapes will erode and evolve, whether they are natural or post-mining. The goal for a post-mining landform is for it to have an erosion rate commensurate with the long-term goals of the landform and not deliver excess sediment to the surrounding unmined landscape. In some cases, where hostile material is buried within the waste (i.e. acid-forming waste rock), a lower erosion rate may be appropriate to ensure the long-term encapsulation of the buried material.

An issue with the design and construction of post-mining landforms is that for many mines, only a small fraction of the material of interest is removed (i.e. gold mines are often profitable at gold concentrations of less than 1 g tonne^{-1}), and the exhumed material has a greater volume than that of the intact material. This means that the post-mining landscape will have a greater volume than the original landscape and will sit above the original surface. The materials, while natural, have been subject to blasting (by explosives) and in most cases have different geochemistry and physical properties (such as particle size, porosity and permeability and can chemically react upon exposure to water and oxygen at many mines) to that of the natural (unmined) surface. This results in a new landscape, which, while subject to the same climate, will be geomorphically very different to that of the original pre-mine surface (Saynor, Lowry, & Boyden, 2018).

A commonly used approach for post-mining landforms is to reconstruct the landscape in a series of linear hillslopes with contour drains or banks positioned at regular intervals according to the site climate, characteristics and erosion properties of the surface material (Hannan, 1984) (Figure 1). This practice follows that of agricultural engineering, where runoff and erosion are managed by constructing a landscape of linear hillslopes, which are practical for agriculture post-mining, as well as being simple to construct.

A concern with such landscapes is that over time, the contour drains are prone to failure as they fill with sediment and erode. Also, if not correctly constructed, they can be subject to gully erosion where concentrated flow erodes a contour drain, leading to cascading failures of the downslope drain as they are unable to cope with the additional runoff (Saynor, Lowry, & Boyden, 2018). Even if correctly constructed, there is always the risk that an extreme event will spill the drain, since designing for very high return periods is not cost-effective. This can lead to severe gully erosion on post-mining landscapes. Linear hillslopes with contour drains are suitable for post-mining landscapes where there will be a continual human presence to manage any erosional failures (Figure 1). However, due to the geographical location of most mines, many of them in remote areas, this is unlikely. Ultimately, it must be recognised that natural drainage lines flow downslope (perpendicular to the contours), and not parallel to the contours.

The above statements do not mean that linear hillslopes are inappropriate for post-mining landscapes. If the slope angle and slope length are appropriate for the material and climate, linear hillslopes can become stable landscapes that integrate within the surrounding non-mined landscape. The leading author has observed this at many sites (Figure 1).

FIGURE 1 An agricultural landscape with contour drains constructed in 1980 with little erosion and receiving some maintenance and repair after a major storm event (top). A post-mining landscape constructed in a series of hillslopes (lifts) with contour drains directing runoff to a rock-lined channel (bottom). All sediment is contained within a sediment pond at the base of the slope. This landscape is hydrologically and sedimentologically disconnected from the surrounding unmined landscape.

A further issue with linear hillslopes is that there are few linear hillslopes in nature. The linear post-mining landscape is visually very different to that of the natural landscape with its regular curvature of hillslopes interspersed with drainage lines. Natural landscapes have evolved according to the underlying geology, climate and resulting vegetation and soil evolution. Community expectations are moving towards a requirement that post-mining landforms, given their scale and often proximity to human population, should have a more natural appearance and functionality (Martín Duque et al., 2021a; Martín Duque et al., 2021b).

The goal of the post-mining landscape is for it to be geomorphically integrated and indistinguishable from its undisturbed surrounds. However, it needs to be recognised that the material and landscape are new and geologically different to the original landscape, and there is very little knowledge as to how the new material will evolve and at what rate. Consequently, assuming the geomorphological success of a post-mining reconstruction is neither a short-term nor a minor consideration. The evolution of the surface and soil development (pedogenesis) may take decades or centuries to occur, with the flora and fauna evolving in concert. A further question is that of starting conditions (i.e. slope length, slope angle and materials) and resultant hydrology and how they influence vegetation and landscape trajectory (Willgoose, 2018).

The question examined here is, how can a new landscape be geo-engineered such that it is visually 'safe, stable and non-polluting', geomorphically optimised, as well as be visually pleasing? New landscapes can be designed using computer-based programs such as AutoCAD with expert knowledge of the climate, materials and final landuse requirements (as the case examined here). More recent innovations use geomorphic design methods (GeoFluv) and the related Natural Regrade software (https://www.carlsonsw.com/product/natural-regrade), which is able to reproduce the complexity of a natural drainage basin, replicating the characteristics of natural drainage networks and related hillslopes while honouring the volume and footprint constraints of a given project. But neither of the above methods takes into account material properties or use any knowledge of likely long-term erosion and deposition processes and patterns, and therefore provides no insight into long-term landscape behaviour.

Computer-based Landscape Evolution Models (LEMs) can be used to develop new landforms (Willgoose, 2018). LEMs are computer-based tools which allow a landscape to be input (in the form of a digital elevation model) and the landscape evolves under the action of erosion and deposition. LEMs require parameters for the hydrology and erosion properties of the site of interest. Given an understanding of the site materials and climate, a proposed landscape design can be input and allowed to evolve.

Using a LEM to evolve a landform allows an understanding of how a landscape may look and geomorphically behave at geological time scales as well as the ability to assess different designs and optimise that design (Hancock et al., 2019). The outcome is for the landscape to have a visual appearance that is in keeping with the surrounds and an erosion rate which approximates that of the surrounding undisturbed landscape and minimises gullying.

The aim of this paper is to demonstrate a new method using a LEM to design a post-mining landform. Three design methods to create a post-mining landform are examined to demonstrate this process. The first design uses 'Expert Knowledge' to build a landscape in the form of a catchment with a designated footprint and volume constraint. That is, the shape and volume of material are fixed and the landscape is created by an engineer with decades of knowledge of the site environment. This is a standard method currently used. The second approach uses a LEM to design the landscapes. This second method uses the catchment boundary and topography of the Expert Knowledge design and uplifts it to that of (a) a planar surface with the drainage network preserved and (b) the Expert Knowledge catchment uplifted and random roughness added to the surface. That is, no drainage network is imposed. These landscapes are then input to a LEM and allowed to evolve until their volume matches that of the Expert Knowledge catchment. The third approach examines that of an uplifted catchment with the same area and length to width (aspect) ratio of the Expert Knowledge catchment. This catchment is in the form of a rectangular box. This landscape is then input to a LEM and allowed to evolve until its volume matches that of the Expert Knowledge catchment. The above LEM-generated landscapes with the same volume as that of the Expert Knowledge catchment are then assessed for their geomorphic form and erosional behaviour (erosion rate and gully depth) with comparison to that of the Expert Knowledge catchment.

The paper describes the design process, the use of LEMs to create new landscapes as well as an evaluation of the landscapes in terms of catchment geomorphic form and function, erosion rate and gully (incision) depth. The outcome is a new methodology to complement existing design methods, as well as producing geomorphically optimised landforms.

2 | METHODS

2.1 | Landscape design

There are four constraints that need to be considered when designing a post-mining landscape: 1. Volume of material; 2. Landscape footprint; 3. Ease of construction; and 4. Material hydrology and erosion characteristics. These factors need to be optimised to produce a set of landforms that comply with the agreed post-mining land use as well as ecologically integrate with the landscape surrounds.

Here, three design methods are examined. The first method and resultant design use Expert Knowledge to fit a landscape (a catchment) with a natural appearance and drainage lines within a designated footprint and volume constraint (Figure 2). That is, the volume of the landscape material is fixed.

The second approach is to use the design created using Expert Knowledge as a template to examine other options such as random drainage network creation. The third method uses the same area as the catchment created using Expert Knowledge, together with the same length-to-width (aspect) ratio to create a rectangular catchment (Figure 3). This removes the complexity of designing a catchment with irregular boundaries. These are described below.

2.1.1 | Landscape design using expert knowledge (CC-EK)

The provided Digital Elevation Model (DEM) is a former proposed design for the rehabilitated landscape for the Corridor Creek catchment at the ERA Ranger Mine (ERARM) in the Northern Territory, Australia. The design provided has been one option for the final landform (Figure 4). The landscape has been described elsewhere (Hancock, Lowry, & Saynor, 2017). The catchment covers tailings which have been placed in a former pit and therefore need to be encapsulated for millennia (Australian Government, 1999). Therefore, developing and testing design options for tailings encapsulation has been a major focus of the landscape design. This landscape design is such that it has the form of a catchment and visually blends in with the surrounding landscape, with sediment exiting from the lowest edge of the catchment. The catchment has an area of 303.1 ha with relief of 26 m and is termed the Corridor Creek Expert Knowledge catchment (CC-EK).

This landscape can be input to a LEM and assessed for its long-term erosional behaviour.

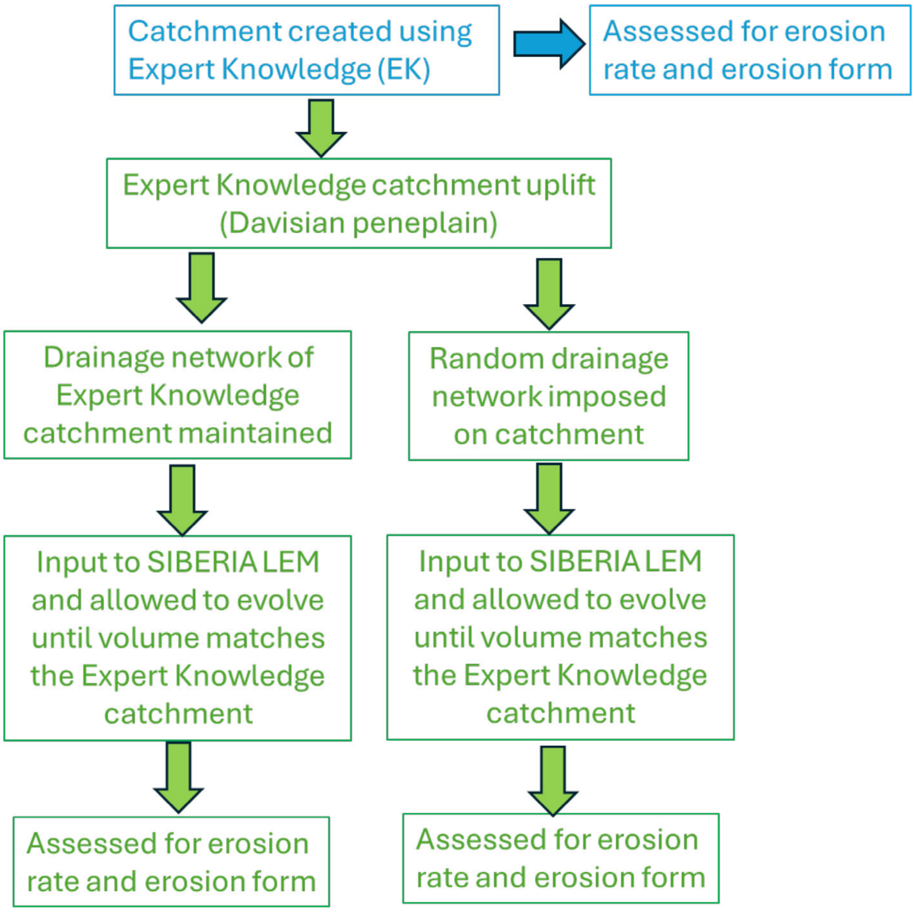

FIGURE 2 Process for constructing and evaluating the post-mining catchments. The catchment created using expert knowledge (EK) (in blue) is evaluated for its erosion rate and form. The expert knowledge catchment provides the area and volume template for the catchments that are input to the landscape evolution model to evolve (in green). Once the volume of these evolved catchments matches that of the expert knowledge catchment, they are assessed for their erosion rate and form.

2.1.2 | Design template approach

The footprint and drainage pattern based on the CC-EK design can be used as a template for the creation of a new landscape with (a) maintenance of the drainage network from the CC-EK catchment and (b) no drainage network imposed (Figure 2).

a. **Maintenance of drainage network**: CC-EK design elevations are normalised (to between a value of 0 and 1 m) and the landscape uplifted to the maximum elevation of the catchment (i.e. the concept of a Davisian uplift) (Figure 5) and described in Hancock (2003). Normalising elevation between 0 and 1 m was sufficient to produce a drainage network; however, a greater normalised elevation range could also be employed (i.e. between 0 and 5 m and is not explored here). A series of low points with the same elevation as that of the non-uplifted CC-EK catchment were placed at the catchment outlet. This approach directs erosion and landscape evolution to occur from the outlet, with landscape evolution occurring upslope from the outlet. This design maintains the original drainage network. This catchment is termed Corridor Creek – network (CC-net).
b. **No initial drainage network**: The CC-EK catchment boundary is used and the catchment is uplifted to the catchment maximum elevation with no preservation of the drainage network (Figure 2). A random elevation of between 0 and 1 m is applied to the surface. A series of low points with the same elevation as that of the non-uplifted CC-EK catchment were placed at the catchment outlet. This approach also directs erosion and landscape evolution to occur from the outlet moving upslope from the outlet. Importantly, no drainage network is imposed. The catchment is termed Corridor Creek –random network (CC-rand).

2.1.3 | Catchment aspect ratio

A rectangular catchment with the same length, width and area as that of the CC-EK catchment was created. That is, the catchment had the same length-to-width ratio (aspect ratio) and the same area as the CC-EK catchment (Figure 3). This landscape with linear boundaries was uplifted to the CC-EK catchment maximum elevation, and a random elevation value of $+/-$ 1 m was applied to the surface. On the bottom (short) side of the boundary, a series of low points with the same elevation and width as that of the CC-EK catchment outlet were placed. This approach directs erosion and landscape evolution to occur from the outlet moving upslope from the outlet. This landscape is termed Corridor Creek – aspect ratio (CC-AR).

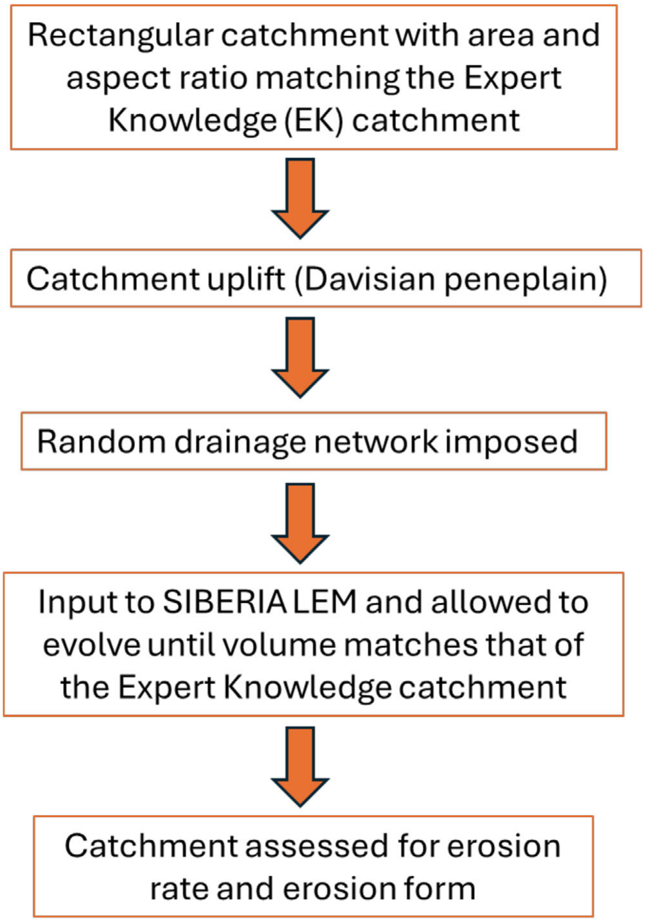

FIGURE 3 Process for constructing and evaluating the rectangular catchment with area and aspect ratio matching that of the expert knowledge design. The expert knowledge design provides the area and volume template for the catchment that is then input to the landscape evolution model to evolve until its volume matches that of the expert knowledge catchment. This is then assessed for its erosion rate and form.

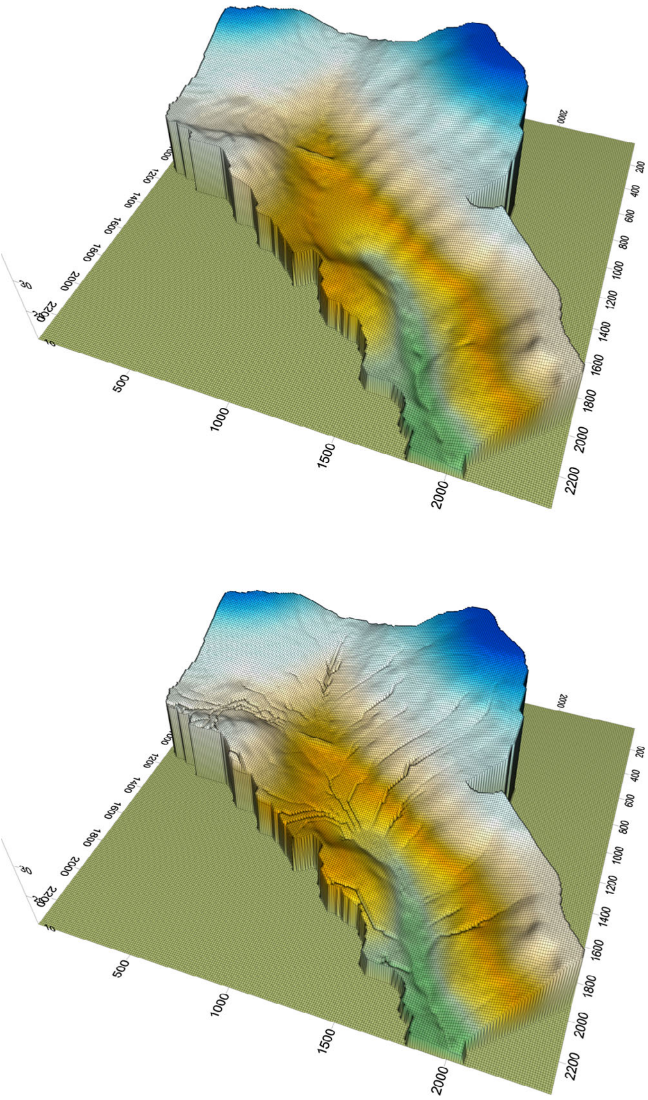

FIGURE 4 Proposed Corridor Creek landscape designed using expert knowledge (CC-EK) (top) and after 100 years of erosion (bottom).

2.1.4 | Catchment boundary condition and modelling

It should be noted that, for all landscapes, a series of outlets is imposed across the bottom of the catchment with the same width as the CC-EK catchment. All sediment is allowed to exit from these outlets at the lowest point in the catchment.

The CC-net, CC-rand and CC-AR are then input to a LEM (SIBERIA – described in Section 2.3 below) and allowed to evolve using site-specific erosion and hydrology parameters until the volume matches that of the CC-EK catchment. This is described in Section 3.

2.2 | Landscape evolution models

In recent decades, a new generation of models that predict both erosion and deposition has been developed. These computer-based Landscape Evolution Models (LEMs) predict both erosion and deposition and evolve the landscape in response to this process. Originally developed to assess landforms at millennial (geological) time (Ahnert, 1976), their usefulness for environmental, geomorphological and engineering applications was rapidly developed. These models operate across a range of spatial and temporal scales and have been applied in both natural (undisturbed by humans) (Hancock, Willgoose, & Evans, 2002) and highly modified post-mining environments (Tucker & Hancock, 2010; Hancock & Willgoose, 2018; Willgoose, 2018).

There are numerous landform evolution models with different strengths, weaknesses and functions (Braun & Sambridge, 1997; Coulthard, 2001; Tucker et al., 2001; Coulthard & Van De Wiel, 2006; Willgoose, Bras, & Rodriguez-Iturbe, 1991a, 1991b, 1991c) with new models being developed, tested and/or updated (Litwin et al., 2023, 2024; Skinner & Coulthard, 2023; Xie et al., 2024). A background to the models can be found in Coulthard (2001), Willgoose (2005), Tucker & Hancock (2010), Murphy, & Evans (2010) and Willgoose (2018).

The rationale for using LEMs to create a landform is that if the model formulation is correct and parameterisation appropriate (for the materials and climate), the resultant landform prediction will be an expression of what the landform may evolve to over geological time. Using this design process, it is assumed that (1) climate will remain static and (2) weathering, climate, pedogenesis and vegetation

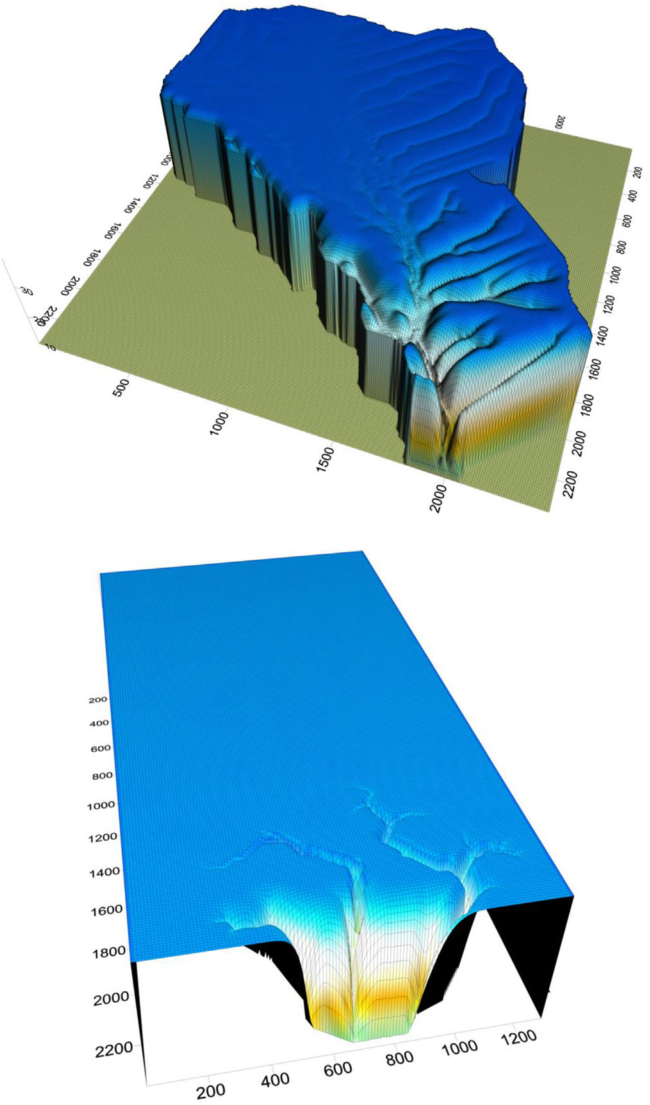

FIGURE 5 Proposed catchment uplifted with normalised elevation (CC-net) after 10,000 years of erosion (top) and rectangular catchment boundary with length to width ratio matching that of the proposed design at 10,000 years of erosion (CC-AR) (bottom).

feedback are constant. Therefore, any modelling is simplistic and cannot take into account the effects of climate and weathering uncertainty over geological time, and any landscape prediction is a reflection of one possible outcome.

2.3 | LEM model and parameters

Here, the SIBERIA model is used (Willgoose, Bras, & Rodriguez-Iturbe, 1991a-c). The SIBERIA model has been well-described elsewhere (Willgoose, 2018), and a summary of the model formulation and application is provided in Hancock and Willgoose (2018).

Parameters for SIBERIA have been previously developed for the study site (Evans & Willgoose, 2000; Evans, Saynor, & Willgoose, 1999; Evans et al., 2000; Hancock et al., 2000; Hancock, Willgoose, & Evans, 2002; Willgoose & Riley, 1998). Here, parameters for 'Waste Rock' (bare surface devoid of vegetation) and parameters for a 'Vegetated' waste rock surface are employed. The full derivation of these parameters is described elsewhere (Evans et al., 2000; Evans & Willgoose, 2000; Moliere et al., 2002). The parameters are displayed in Table 1.

TABLE 1 SIBERIA parameter values for each region of the ERA ranger mine.

	m_1	n_1	β_3	m_3	β_1
Waste rock	2.52	0.69	0.00016	0.81	2,243
Vegetated waste rock	1.59	0.69	0.000006	0.9	2088

3 | MODEL SETUP, LANDSCAPE CREATION AND LANDSCAPE EVALUATION METHOD

3.1 | Creation of new catchments

The CC-EK catchment is a proposed design and was evaluated for its erosional performance as supplied (Figure 4).

As described in Section 2.1, the CC-EK catchment was used as a design template to create a series of new catchments based on the CC-net, CC-rand and CC-AR templates (Figure 5). To create the new design options, the CC-net, CC-rand and CC-AR were input to the SIBERIA LEM and were run using the Waste Rock surface parameters and allowed to evolve until the average elevation of the landscape matched that of the CC-EK landform (Figures 6-8).

3.2 | Landscape design assessment

In terms of catchment shape, area and elevation, the CC-EK, CC-net and CC-rand catchments have fixed boundaries which the initial starting conditions define. Evaluation of the evolved landforms (Figures 6–8) was performed firstly by qualitative or visual assessment. That is, how does the catchment look in terms of hillslope form and depositional features? Geomorphically, the catchments can be described by the hypsometric curve (Strahler, 1952, 1964). The hypsometric curve and integral (Langbein, 1947) is a non-dimensional area-elevation curve. The non-dimensionalisation of the curve allows ready comparison of catchments with different area and steepness.

3.3 | Landscape erosional performance

The CC-EK (Figure 4) and the evolved CC-net, CC-rand and CC-AR landscapes (Figures 6–8) with average elevation matching the CC-EK catchment were then input to SIBERIA and run for 100 years using (1) Waste Rock and (2) Vegetation parameters (Table 1). 100 years is considered sufficient time for reliable erosion patterns and rates to be determined. Landscape strengths and weaknesses are able to be observed within this period (Hancock, Lowry, & Saynor, 2017a). 100 years is also within a human management time frame, within which any erosion problems can be addressed.

The model predictions were compared to field-derived erosion data. Reported denudation rates for the general area are 0.062–0.088 mm yr^{-1} with this data being a goal for the post-mining

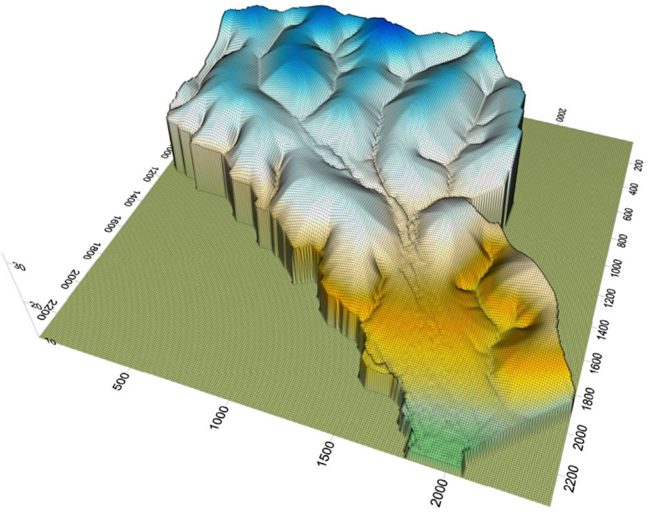

FIGURE 6 Landscape created by the SIBERIA LEM using the same drainage network as the proposed design above in Figure 1 (CC-net). All dimensions are metres.

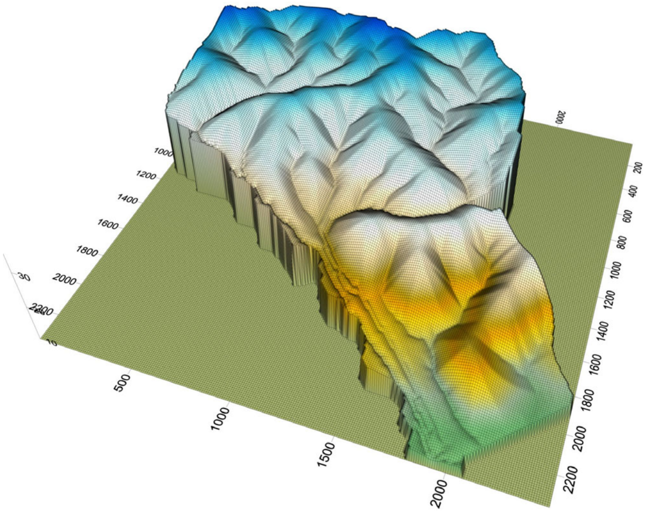

FIGURE 7 Landscape created by the SIBERIA LEM with random numbers (CC-rand) and no drainage network. All dimensions are metres.

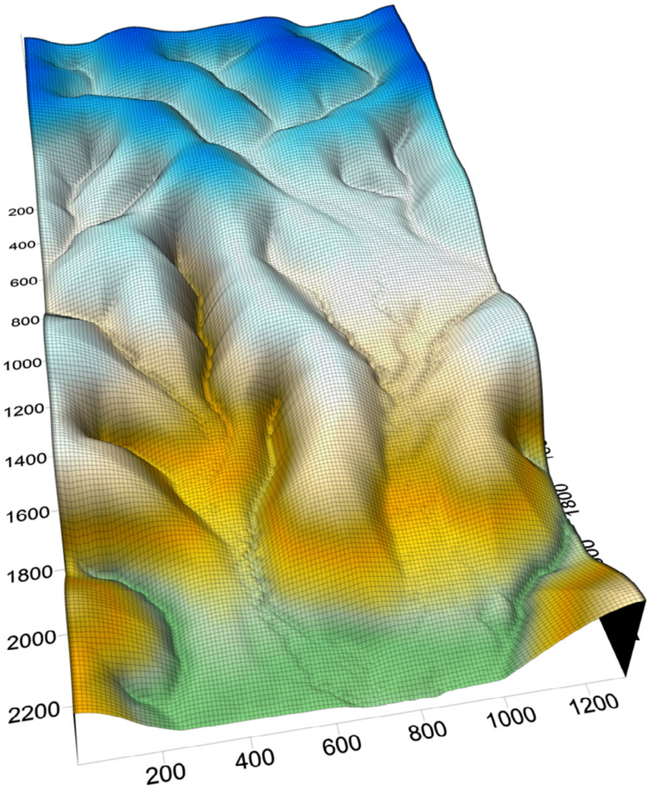

FIGURE 8 Catchment with length and width ratio matching that of the proposed design (CC-AR) (top) and after 100 years of erosion. Gullies can be observed in the main drainage lines. All dimensions are metres.

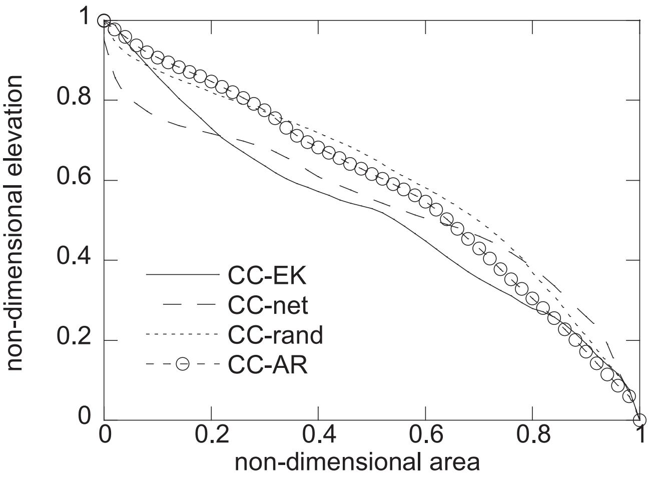

FIGURE 9 Hypsometric curves for the CC-EK, CC-net, CC-rand and CC-AR catchments.

landscape (Wasson, Saynor, & Lowry, 2021). The presence of gullies and gully depth is also an important concern, as radioactive waste and contaminants need to be contained within the site for 10,000 years post-mining (Australian Government, 1999). Hence, gully presence or absence and depth of gullying is used to compare landscape designs; however, the authors recognise that gullies have many other implications for geomorphology and landscape evolution (Valentin, Poesen, & Li, 2005).

4 | RESULTS

4.1 | Proposed Corridor Creek design (CC-EK)

The CC-EK catchment has the appearance of a natural catchment with a main drainage line and long sloping hillslopes delivering water and sediment to this drainage line (Figure 4). Geomorphically, the catchment has a 'youthful' to 'mature' hypsometric integral and curve (Figure 9, Table 2) (Strahler, 1952, 1964).

Sediment output for the catchment varies from year to year in response to the changing drainage network as a response to erosion and deposition (Figure 10). After 100 years of erosion, deposition and landscape evolution, the CC-EK landscape has an average catchment export of sediment of 497 m^3 yr^{-1}. While annually variable, sediment output remains well above the target erosion rate for the 100-year modelled period (Figure 10). This is equivalent to a denudation rate of

TABLE 2 Erosion and denudation rates, maximum gully depth and catchment hypsometry for the Corridor Creek created by expert knowledge (CC-EK), uplifted catchment with imposed drainage network (CC-net), uplifted catchment with random drainage network (CC-rand) and the catchment with the same aspect ratio as the CC-EK design (CC-AR). The CC-EK-100 is the Corridor Creek created by expert knowledge (CC-EK) after 100 years of erosion used as the starting landscape.

	CC-EK	CC- net	CC-rand	CC-AR	CC-EK-100
	Waste rock				
Denudation rate (mm yr^{-1})	0.40	0.027	0.045	0.063	0.20
Max gully depth (m)	2.7	0.62	0.91	0.61	0.94
	Waste rock with vegetation				
Denudation rate (mm yr^{-1})	0.037	0.05	0.05	0.062	0.04
Max gully depth (m)	0.4	0.23	0.5	0.28	0.23
Hypsometric integral	0.51	0.54	0.539	0.58	0.51

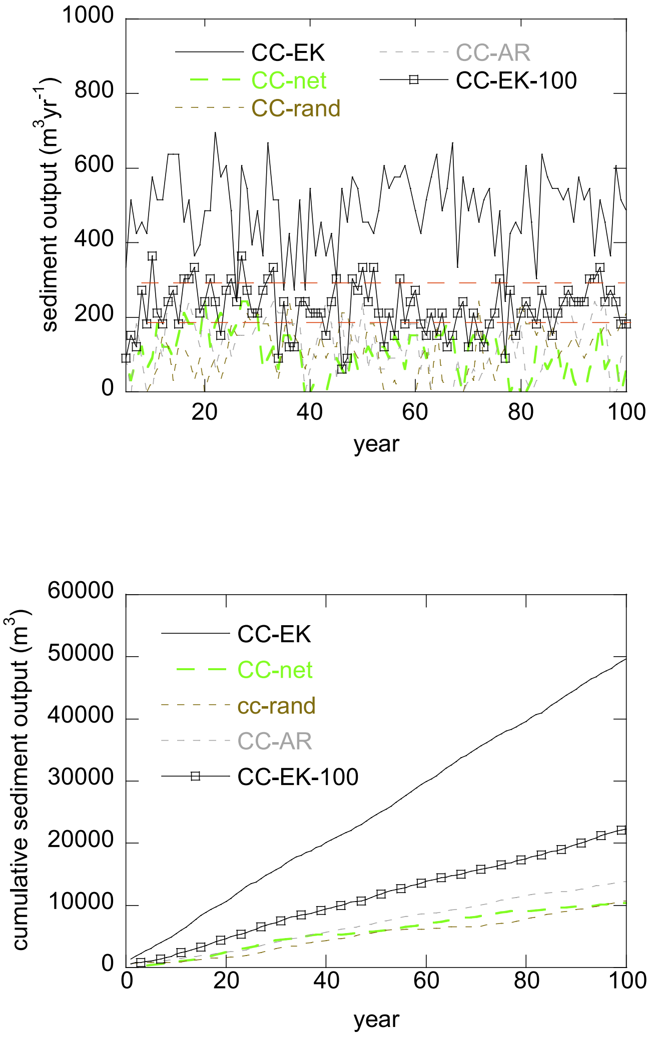

FIGURE 10 Annual sediment output from the CC-EK, CC-net, CC-rand and CC-AR catchments (top) and cumulative sediment output (bottom). The red dotted line represents the natural landscape denudation rate range for the catchment and the target erosion rate.

0.40 mm yr^{-1}, which is well above 0.062 to 0.088 mm yr^{-1} suggested by Wasson, Saynor, & Lowry (2021) as a natural or background range. After 100 years, the landscape has developed gullies in the main channel with some migrating up the hillslope. These gullies have a maximum depth of up to 2.7 m.

Assuming a constant vegetation cover for the 100 years reduces the erosion and denudation rate (0.037 mm yr^{-1}) and gully depth (0.4 m) in comparison to the Waste Rock surface (Table 2).

An option for a proposed landscape design assessment is to take any planned landform and assess it using a LEM for 100 years as described here. However, any proposed design may have features on its surface such as roughness due to gridding, which may enhance erosion. Therefore, the erosion and deposition rate and processes may not correctly represent reality. However, this eroded landform (here after 100 years of evolution) with minimal overall landscape change in landscape volume can still be used as a design surface and assessed using a LEM.

To further evaluate whether the CC-EK design would produce less erosion over time, the 100 year predicted landform was used as the starting landscape and, using Waste Rock parameters (Table 1), run for 100 years (i.e. Figure 4, bottom). This landscape, named CC-EK-100, produced a reduced sediment output of 284 m^3 yr^{-1} with a denudation rate of 0.2 mm yr^{-1} (Table 2), this being approximately half that of the CC-EK landscape and well above that of the target denudation rate. Gully depth was also reduced. Using Vegetation parameters reduced erosion to that of the target range and also reduced gully depth. These results demonstrate that even with 100 years of erosion, the CC-EK landscape design does not produce a denudation rate within the target range and will rely on vegetation to achieve this goal.

4.2 | Design template approach

Evolution of the CC-net and CC-rand catchments commenced at the catchment outlet with a headcut migrating upslope (Figure 5). Over time, the headcut and channel network fill the catchment, and the landscape then lowers. Landscape evolution continued until the average elevation of the catchments matched that of the CC-EK landform (Figures 6 and 7).

The CC-net and CC-rand landscapes, with volume matching that of the CC-EK catchment, have a complex surface with a well-defined series of subcatchments feeding into a main channel. In all cases, the landscapes have the visual appearance of a natural catchment with well-rounded hillslopes and regular channel spacing and valleys in accordance with what qualitatively could be expected for a natural catchment.

The CC-net catchment has evolved to include a large depositional area at the catchment outlet. The CC-rand catchment has evolved to a much more complex landform with hillslopes covering the entire catchment with a complex drainage network. Geomorphically, the catchments are 'youthful' to 'mature' (Figure 9, Table 2).

The evolved CC-net and CC-rand catchments were then input to the SIBERIA LEM using (1) Waste Rock and (2) Vegetation parameters. Waste Rock parameters for the CC-net catchment produce a sediment export of 84 m^3 yr^{-1} (0.027 mm yr^{-1}), and the CC-rand catchment produced 135 m^3 yr^{-1} (0.045 mm yr^{-1}), which are below and or within the natural denudation range (Wasson, Saynor, & Lowry, 2021). As for the CC-EK catchment, sediment export from the CC-net and CC-rand was variable from year to year (Figure 10). Maximum gully depth at 100 years for the CC-net and CC-rand catchments is 0.62 and 0.91 m, respectively.

Using Vegetation parameters reduces the denudation rate for both the CC-net and CC-rand catchments (0.05 mm yr^{-1}) to within the target denudation range with a corresponding reduction in gully depth.

4.3 | Aspect ratio

As for the CC-net and CC-rand catchments, the CC-AR catchment evolved from the headcut at the catchment outlet, with gullies migrating headwards to fill the catchment (Figure 5). As for the CC-net and CC-rand catchments, once the network filled the catchment area, the landscape slowly lowered. The rectangular boundary catchment had a complex landscape, with hillslopes covering the majority of the landscape surface except for a small area at the catchment outlet, which is relatively flat (Figure 8). The catchment has a complex drainage network with two main channels filling the catchment. There is a small depositional area at the catchment outlet. Geomorphically, the catchment is 'youthful' to 'mature' (Figure 9, Table 2).

CC-AR produces an erosion rate of 191 m^3 yr^{-1}, which is a denudation rate of 0.063 mm yr^{-1}. Gullies are present in the main channel, with a maximum gully depth of 0.61 m at 100 years. Using vegetation parameters reduces the erosion and denudation rate (0.06 mm yr^{-1}) and also reduces maximum gully depth.

5 | DISCUSSION

The design and construction of post-mining landforms is a complex undertaking where any structure requires integration with underlying materials and surrounding unmined or undisturbed landscape. For the majority of mines globally, this reshaping has been that of linear hillslopes with imposed drainage structures to manage runoff (Figure 1). Few have committed to a catchment-based reconstruction approach or that employing geomorphic design (Martín-Moreno et al., 2018; Zapico et al., 2018).

The method for catchment design here has employed a simple strategy of that of an uplifted catchment being allowed to evolve until the volume matches that of the proposed design. That is, the landscape has eroded to have a catchment form and function of a youthful to mature catchment. The use of geomorphic design methods for the reconstruction of post-mining landforms has been well-documented and recognised as an effective approach, and the method demonstrated here provides an alternative to that of using GeoFluv (Bugosh & Epp, 2019; Martín Duque et al., 2021a; Martín Duque et al., 2021b).

Here, a series of potential post-mining landscapes are designed and tested using a LEM. Assuming that the LEM itself is correct and its input parameters are correct, then the LEM prediction can be assumed to be 'somewhat' correct. Given this assumption, the landscape prediction should be a reflection of what the landscape may evolve to. This evolved landform, if it (1) has an erosion rate and form acceptable and complementary with the surrounding landscape and final landuse, (2) is visually acceptable and (3) is able to be constructed, provides an option for a post-mining landscape design.

5.1 | Landscape evolution and erosion

All landscapes produce sediment output that varies from year to year (Figure 10). This is in response to the drainage network continually evolving in response to erosion and deposition, delivering sediment to the outlet in a spasmodic pattern. This spasmodic pattern mimics natural processes where sediment is distributed and delivered in what are called sediment slugs (Knighton, 1998; Willgoose, 2018). Of the designs evaluated, the landscape created by expert knowledge produces the highest erosional output, as well as having the deepest gullies. The CC-EK landscape produces sediment output above background erosion rates, as well as having maximum gully depths of up to 2.7 m. Overall, the modelling demonstrates that using the evolved designs (CC-net, CC-rand) produces erosion rates that are one-third to half that of the supplied (CC-EK) design with a commensurate reduction in maximum gully depth. Results demonstrate that a catchment with a series of smaller catchments and a more complex drainage network produces less sediment output.

It is not possible that the surface will be completely devoid of vegetation for 100 years, nor will the surface have a complete vegetation cover. However, assuming constant vegetation greatly reduces the erosion rate and gully evolution. All landscapes assuming constant vegetation have a denudation rate at or below that of the target range. Therefore, the options here (bare surface or vegetated) provide two end members of the likely scenarios. For the Waste Rock parameter simulations, the CC-net, CC-rand and CC-AR all provide erosion and denudation rates within that of background erosion data (Wasson, Saynor, & Lowry, 2021). They also have low gully incision depths.

The design using rectangular boundaries (CC-AR) and using Waste Rock parameters produces a higher denudation rate than that of the irregularly shaped boundary catchments (CC-net and CC-rand); however, it has a denudation rate within the target range and low gully incision depth. While a catchment with a rectangular fixed linear boundary will never occur in nature, the findings here suggest that catchment shape is not critical in obtaining acceptable erosion rates and low incision depth. The modelling shows that subcatchments will evolve with a form that approximates that of natural hillslopes and with the same form as that of the proposed designs here. Therefore, for catchment design, while the landscape footprint may be fixed, together with landscape volume, boundary shape (whether it be regular or irregular) may not be that important for internal catchment evolution and resultant geomorphology (including erosion rate and erosion form). Hancock (2003) and Willgoose, Hancock, & Kuczera (2003) examined this aspect ratio concept using a natural catchment and found that an irregularly shaped catchment boundary is not critical for a landscape to be geomorphically equivalent (using the area-slope relationship and hypsometry as the tools for catchment equivalence or otherwise).

The hypsometric curve can be used as an indicator of the geomorphic maturity of catchments (Strahler, 1952, 1964; Langbein, 1947). Willgoose & Hancock (1998) demonstrated its linkage with erosion processes, catchment geometry and network form. Strahler (1952, 1964) classified landforms into youth, mature and monadnock characteristic curves, indicating increasing catchment age. An advantage of this approach is that it is not greatly affected by random aspects of the channel network while still being sensitive to changes in the parameters of the erosion physics. While the curves here vary from youthful to mature, a more strongly mature form may be obtained by employing a LEM with dynamic uplift and allowing the landscapes to evolve to the volume of the CC-EK catchment. This is the focus of future work.

Here we find that the CC-EK catchment has the smallest integral (0.51) with CC-net, CC-rand and CC-AR having higher integrals, indicating that even though they have the same volume as CC-EK, they are less mature. This suggests that the CC-net, CC-rand and CC-AR evolved landscapes with their multiple drainage lines and subcatchments, and the resultant drainage network configuration has a greater influence on erosional output than landscape maturity. That is, the drainage network form overrides geomorphic maturity (as indicated by the hypsometric curve) in regard to the erosion rate.

5.2 | Landscape design and model parameters

All designs were assessed using 2 sets of parameters, one representing a bare surface and high erosion (Waste Rock) and a second representing a vegetated surface and low erosion (Vegetation). The assessment assumed a bare surface and then that of a vegetated surface for the 100-year model run. These represent opposite ends of the potential erosion spectrum.

Many current post-mining landscapes are reliant on vegetation for their erosional stability, such that successful rehabilitation is equated to successful revegetation. Stiller, Zimpfer, & Bishop (1980) stated 40 years ago that successful rehabilitation includes revegetation, but that “revegetation and erosion control are not simply cause and effect”. A natural landscape, even if fully covered with vegetation, always has drainage lines to direct runoff. This is a supporting evidence for a “catchment” approach to mine rehabilitation (Sawatsky & Beckstead, 1996; Toy & Chuse, 2005).

While the results here clearly demonstrate the erosion reduction potential of vegetation, any landscape system should have topography that is erosionally stable, with vegetation providing the foundation for ecological succession. Any reliance only on vegetation is a high-risk strategy as there is no guarantee of regular rainfall to maintain acceptable vegetation covers (Evans et al., 1998, 2000; Evans, Saynor, & Willgoose, 1999; Evans & Willgoose, 2000; Stiller, Zimpfer, & Bishop, 1980). The study area is prone to fire with a return interval of 1 every 2 to 5 years, and loss of vegetation is a serious consideration.

Therefore, a LEM with material and climate-specific parameters allows any design to evolve with a more robust set of parameters and boundary conditions. A disadvantage of using site-specific parameters developed over relatively short time periods is that it is unknown how they will change in response to weathering, climate and vegetation interactions over time. At present, there is much qualitative data but little quantitative data available on weathering rates and processes for post-mining materials. There is also a paucity of data on other influential aspects, such as armouring and pedogenesis. Models such as SIBERIA have an armouring function that can be employed at sites where the armour model can be parameterised (Hancock et al., 2017). CAESAR-Lisflood develops a surface armour as a result of overland flow and use of a user-defined particle size distribution and active erosion depth (Coulthard et al., 2013). More recent models such as SSSPAM incorporate both weathering, armouring and pedogenesis at any user-defined horizon interval and depth (Welivitiya, Willgoose, & Hancock, 2019). Climate variability and vegetation response, together with the role of fire, are also significant concerns for erosion and landscape response, with CAESAR-Lisflood and SSSPAM being able to use temporally variable rainfall input to represent potential climate extremes and landscape response (Evans, Saynor, & Willgoose, 1999; Evans et al., 2000; Willgoose, 2018). Field and laboratory data is now needed to both parameterise and validate these models (Welivitiya & Hancock, 2024).

5.3 | Further considerations

5.3.1 | Landscape construction

This study has examined catchment design as the sole method for increasing erosional stability (reducing erosion). Over the short-term, erosion can be reduced by the introduction of rock armour in channels which over time have become vegetated as well as the addition of surface roughness via ripping (Saynor, Lowry, & Boyden, 2018). The authors recognise that in many cases, engineering methods may be required to manage runoff and erosion. These field-based erosion reduction strategies can be tested using a LEM (Figure 1, bottom).

The method for catchment design here has employed a simple strategy of an uplifted catchment being allowed to evolve until the volume matches that of the proposed design. An alternative method could be to use a linear sloping surface with maximum elevation at the highest point in the catchment, matching that of the proposed design, with elevation regularly lowering towards the outlet. This would force all runoff immediately downslope and towards the outlet. A further option would be to add 5 m (or additional volume of material evenly spread over the surface) of elevation to the CC-EK design and allow this landscape to evolve. However, this approach is likely to have elevations at or near the boundary that exceed agreed and enforceable post-mining design considerations.

While the evolved landforms produce less erosion and less gullying, it is recognised here that the evolved landforms are more technically difficult to construct. However, with computer-guided machinery, constructing such complex landforms is now possible. Alternative methods, such as using the GeoFluv method (and related Natural Regrade software), may also provide alternative landscape designs.

5.3.2 | Modelling practicalities

Soil erosion assessments have long been conducted using models such as the USLE and variants and newer models such as WEPP for many decades (Brooks et al., 2014; Evans, 2000; Evans & Loch, 1996; Hazelton & Murphy, 2007; Wischmeier & Smith, 1978). These models have been applied and tested in many environments globally and are useful and valuable tools. They have been used extensively to support the design and assessment of post-mining landforms. As for LEMs, they require field-based parameters for reliable use. These models are soil erosion prediction tools only, with an erosion rate provided with no information on the erosion process and therefore do not evaluate the landform or provide information on gully risk. Therefore, any prediction from such models should be used as a soil loss guide only, as they provide little information on the erosion process and, in particular, gullying, which is of high interest for post-mining landforms. However, for basic soil erosion assessments, they are quick and easy to run and reliable.

A further issue for the design approach is that it takes ∼100 hr of computer run time for the landscape to evolve to the required volume for a 300 ha landscape using a 10 m DEM grid examined here. This requires multiple computers to assess different design and parameter sets and is therefore not a quick process. Larger landscapes will take longer to run. However, it may be possible to assess a simple landscape at a coarser DEM grid scale depending on landscape complexity. This would reduce the time required for the modelling.

6 | CONCLUSION

Post-mining landscapes will have a legacy that will last for millennia. Technology is available to design and construct these new landforms in such a way that they geomorphologically integrate into the surrounding undisturbed landscape. The process here, using a LEM to determine a likely landscape erosional trajectory, is a new method for landscape design.

The findings here demonstrate that a conventionally designed landscape can produce low and acceptable erosion rates only with a consistent vegetation cover. However, a landscape should not solely rely on vegetation for erosional stability.

The landform design created by the LEM using a given set of hydrology and sediment transport parameters produces a more erosionally stable landform. The inclusion of vegetation reduces erosion further. Designs constructed using a LEM all produce erosion rates within acceptable natural background levels. Further, landscapes with smaller sub-catchments and a more complex drainage network produce less erosional output and lower gully depths.

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