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Designing, building and assessing a geomorphically reconstructed postmining landscape: A case study of the Santa Engracia mine, Spain

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Abstract

New technology allows the reconstruction of postmining landforms using geomorphic design principles. It is important that such designs be evaluated and if needed, redesigned or reshaped so that soil loss is minimised and to ensure the landscape is geomorphically and ecologically integrated with the surrounding landscape. One tool to assess geomorphic landforms is to use a computer-based landscape evolution model (LEM). LEMs allow different designs to be input and will highlight where erosion will occur and type of erosion (i.e. sheetwash, riling, gullying) as well as erosion rate. At the Santa Engracia abandoned mine (East-Central Spain), postmining landscapes were designed using geomorphic principles (GeoFluv method and Natural Regrade software) and later constructed. The SIBERIA LEM was used to assess the erosional behaviour of these landscapes. Using suitable topsoil, vegetation and an organic blanket reduces erosion, and if vegetation can be established, the modelling demonstrates minimal gully erosion. The erosion forecast (5.3 to 6.3 t ha^{-1} year^{-1}) is significantly lower than the initial surface (~350 t ha^{-1} year^{-1}) using conventional (terraced) mine restoration. The predicted erosion rates and gullying are less than for the unmined (natural) Alto Tajo environment. Importantly, with the ability to spatially forecast gully location, erosion reduction measures can be undertaken. The method described here provides a robust assessment procedure and highlights the potential strengths and weakness of a design therefore supporting lower cost construction and repair with a higher chance of restoration success. The combination of geomorphic landform design and assessment using a LEM for this project (LIFE RIBERMINE) presents a new standard for mine rehabilitation in Europe.

KEYWORDS
GeoFluv, geomorphic landform design, geomorphic restoration, gully, SIBERIA

1 | INTRODUCTION

Improved solutions for degraded land restoration are needed. There is growing recognition that geomorphology can provide enhanced environmental outcomes for sites that have been subject to large-scale earth movement (Hancock et al., 2020; Hannan, 1984; Stiller et al., 1980; Toy & Chuse, 2005). The use of geomorphic understandings and practice (which includes theory, design, software development, modelling, construction and monitoring) is aimed at developing alternative approaches to traditional engineered (graded, linear) landforms in land rehabilitation (such as contour banks or terraces and down-drains) (Bugosh & Epp, 2019; Sawatsky et al., 2000; Sawatsky & Beckstead, 1996).

Geomorphic solutions are an area of high interest for postmining landscapes, as there are many failures (i.e. landslides, high erosion rates and low ecological integration with surroundings) of many postmining landscapes due to poor landscape design and construction. In Europe, due to the aftermath of two major accidents involving the spill of hazardous extractive waste (one in southwest Spain in 1998), the Mining Waste Directive 2006/21/EC was adopted at EU level with the aim to prevent, or reduce as far as possible, the adverse effects from extractive waste management on health and the environment. Further, and importantly, hydrological, ecological and visual integration and connectivity with the unmined environment are often not, or only partially, considered. A postmine landscape is increasingly functional when it is hydrologically integrated with its environment (SMCRA, 1977). There is also a growing demand by the public requiring that rehabilitation structures hydrologically and visually blend with the surrounding landscape (NSW Resources Regulator, 2021) and have the potential to support maximum possible biodiversity.

While the concept of using geomorphic understandings to design a new landscape is not new and conceptually straightforward (i.e. recognising that the catchment is the most suitable land restoration unit—not linear hillslopes with linear constructed drains), the capabilities for designing such complex 3D landforms and drainage networks are nontrivial and has only recently become possible with the development of geomorphic design software (Bugosh & Eckels, 2006). Methods such as GeoFluv, through the Natural Regrade software, a focus of the work here, provide this capability. A second difficulty is the physical construction of such complex landforms and landscapes, which is now possible with GPS-guidance machine control on large earth moving equipment (Bugosh & Eckels, 2006).

However, designing a landscape is one-half of the process. A new landscape should be robustly evaluated for its erosional stability. Without long-term field plots of different slope angles and lengths (together with assessment of different materials both at the surface and underlying) which are not practical for many sites, numerical soil erosion and landscape evolution models (LEMs) provide a tool to evaluate designs (Evans et al., 1999, 2000; Evans & Willgoose, 2000). What is needed is a rigorous method for testing landscape designs. There are many mines that have been abandoned either legally or illegally and are now a legacy and an environmental and economic burden for the community. New landform design methodologies are useful to aid in the successful restoration of these sites (such as the study site that we describe here).

There are several numerical models that can be used to assess soil erosion and landscape evolution (Coulthard et al., 2013; Tucker & Hancock, 2010; Willgoose, 2018). Here, we focus on computer-based LEMs. Originally developed in the 1970s (Ahnert, 1976), these all use a digital elevation model (DEM) or mesh of grid cells to represent a catchment (Coulthard et al., 2012, 2013; Willgoose, 2018; Willgoose et al., 1991a, 1991b). These numerical models employ both fluvial and diffusive erosion processes together with climate expressed in rainfall amount and intensity (Cache et al., 2023). These models are particularly useful for assessing postmine landscape designs, as they can be input into the LEM and allowed to evolve. Models such as SIBERIA and CAESAR-Lisflood (Coulthard et al., 2012, 2013; Hancock & Willgoose, 2018; Willgoose, 2018) are ideal for assessing landscapes at annual time steps and can be run up to thousands of years (Hancock et al., 2016). CAESAR-Lisflood is run at hourly time steps and requires hourly rainfall as input. It is particularly useful where the focus is on storm scale runoff and erosion and hourly rainfall data is available. SIBERIA is parameterised to be run at yearly time steps and is suitable for sites where longer term landscape assessment is required and does not require rainfall time series as input. In this study, the SIBERIA model is used.

Here, geomorphically designed landforms are assessed using the SIBERIA LEM at the Santa Engracia mine in East Central Spain, within the LIFE RIBERMINE project. The site setting and erosion processes are described followed by the landscape design process. A range of potential surface treatments for the design outcomes (vegetation, erosion control mats) are examined. The final geomorphic designs are described and assessed, and LEM model results are reported in terms of erosion type, erosion rate and potential erosion location. The strengths and weaknesses of the designs and surface treatments are examined and highlighted.

2 | SITE DESCRIPTION

2.1 | Physical environment

The site is located at the edge of the Alto Tajo Natural Park, in the Iberian Mountain Range, East-Central Spain (Figure 1), within a Natura 2000 Network site and also within the Comarca de Molina-Alto Tajo Geopark by UNESCO (http://wwwgeoparquemolina.es). A detailed description of the site is provided elsewhere (Martín-Moreno et al., 2018; Zapico et al., 2018). The landscape is characterised by plateaus and mesas (circa 1400 m above sea level) capped by Cretaceous carbonates (limestones and dolostones), in which the Tajo River (circa 1000 m above sea level) has sculpted a canyon system over 100 km in length. Underlying the carbonates is sandy sediment that holds high-quality kaolin (Arenas de Utrillas Formation) extracted at several mines (Figure 2a) in the so-called Poveda de la Sierra–Peñalén Mining District. The most common soils in the area are calcaric cambisols, mollic leptosols and rendzic leptosols on top of the mesas, and calcaric cambisols on carbonate colluvia on the slopes (IUSS Working group WRB, 2007). The vegetation is representative of Mediterranean continental environments, with forest communities dominated by black pine (*Pinus nigra* subsp. *salzmanii*), gall oak (*Quercus faginea*) and savin (*Juniperus thurifera*). The climate is temperate Mediterranean with dry, mild summers with a noticeable continental influence. The mean annual precipitation is 780 mm, and mean annual temperature is 10°C. The seasons are characterised by long, cold winters, commonly with snowfalls, and short dry summers with high intensity rainstorms. Spring and fall are usually wet. The rainfall erosive conditions are among the highest in the Iberian Peninsula (see Martín-Moreno et al., 2018).

2.2 | The LIFE RIBERMINE project: A solution for severe hydrologic impact

The work here was conducted as part of a European Union LIFE RIBERMINE project (https://liferibermine.com/en/homepage_en/) employing geomorphic-based mine restoration actions in Spain and Portugal. In Spain, the landscape reconstruction centres on abandoned kaolin mines of Peñalén (Guadalajara Province). Specifically, the restoration focuses on the ancient Santa Engracia mine, which creates extremely poor water quality downstream (discussed below), and it is the main site to be restored within the LIFE RIBERMINE project (Figure 3).

The prerestoration scenario evolved from a conventional (terraced) restoration of unconsolidated fill material in 1990 (Figure 2c) to a heavily gullied hillslope (badland) with an erosion rate

FIGURE 1 Study area—location of the Santa Engracia mine, Peñalén municipality, within the Guadalajara province, Castile-La Mancha Region. The mine is located within the Iberian Mountain Range, at the head of the Tagus (Tajo) river basin, at the edge of the Alto Tajo Natural Park. [Color figure can be viewed at wileyonlinelibrary.com]

of 353 t ha^{-1} $year^{-1}$ (Martín-Moreno et al., 2018) in 2020 (see Figure 2e–f). The sediment yield from these highly eroded waste dumps constructed of unconsolidated fill material is hydrologically connected with the Tajo River, within the Alto Tajo Natural Park, and has resulted in extremely poor water quality in terms of suspended sediment concentration (SSC) (Figure 3). Specifically, Zapico et al. (2017) measured up to 391 g L^{-1} of SSC downstream of these mines, whereas the SSC baseline for this fluvial system in the absence of mining influence is 24 g L^{-1} (Zapico et al., 2017). This siltation, which affected aquatic fauna and flora and spawn areas, was the most critical environmental problem of the Alto Tajo Natural Park. Also, before the LIFE RIBERMINE project, an initiative with a budget of close to 1 M€ built three check dams downstream of the Santa Engracia mine, but was ineffective at controlling the sediment yield from the mine site, since they were filled with sediments in a few months (see Martín-Moreno et al. [2018] for a detailed description). Therefore, the goal of LIFE RIBERMINE project was to remove the source of sediment entering the Tajo River fluvial ecosystems, by ecological, geomorphic-based restoration of the Santa Engracia mine.

2.3 | Geomorphic landscape design and construction

For the design of rehabilitation landforms on the unconsolidated waste dumps at the Santa Engracia mine, the GeoFluv method, through the Natural Regrade software, was used (Figures 4 and 5). GeoFluv is a method for landscape design that aids the user to create landforms that naturally would form by fluvial erosion processes under the site climate and physical conditions. Inputs are derived from a stable reference area suitable for the site conditions and final land-use (https://www.carlsonsw.com/product/natural-regrade). The Natural Regrade software allows users to create and assess landscape designs. A description of the method is provided elsewhere (Bugosh & Epp, 2019; Martín Duque, Tejedor, et al., 2021a; Martín Duque, Zapico, et al., 2021b; Zapico et al., 2018). An overall view of the preconstruction and final geomorphic landform design is displayed in Figure 4. The East Waste Rock Dump (EWRD) allowed designing a fluvial channel flowing in the maximum gradient direction, which is the most frequent geomorphic scenario. However, the high steep slope gradients of the West Waste Rock Dump (WWRD) led to the development of a new landform restoration approach for sidehill waste rock dumps (see Orman et al. [2011] for such WRD typology). This new topographic geomorphic restoration solution, described here for the first time, consists of transforming a typical platform-outslope topographic model (Figure 5a) into a transverse catchment and a scalloped hillslope. The solution consists of opening a transverse valley, parallel to the contours of the original slope and incorporating a drainage line optimally tied in elevation and slope gradient to an appropriate base level. The upper hillslope of the valley accommodates the volume of material from the valley that needs to be excavated, whereas the original outslope is transformed into a convex-concave scalloped hillslope by moving earth downhill, connecting the rehabilitated subridges (noses) and swales (hollows) with those existing at the natural slope. Between the bottom of the valley and the scalloped hillslope, a small divide provides a transition

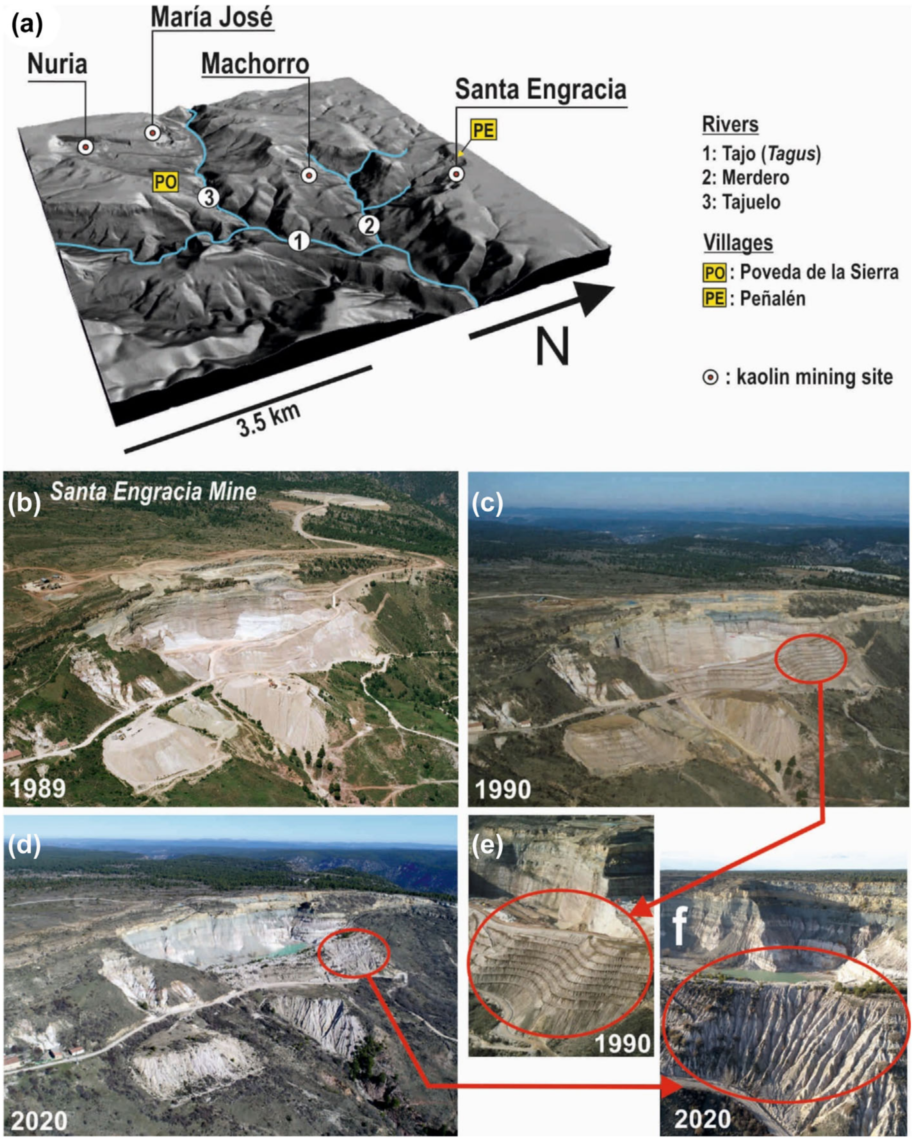


FIGURE 2 (a) 3D model showing the physiographic setting of the main mined sites at the Poveda de La Sierra–Peñalén Mining District. (b to f) Santa Engracia mine. (b) Oblique aerial view of 1989—a sidehill waste dump building process, close to completion (image by Paisaje Españoles). (c) Site in 1990, initially restored phase (image by Paisaje Españoles). (d) Site in 2020, showing 30 years of erosion evolution (image by DIEDRO). (e–f) Detailed comparison showing the severe gullying-badland erosion which occurred after restoration, from 1990 (e) to 2020 (f) (1990 image by Paisajes Españoles, 2020 image by DGDRONE). [Color figure can be viewed at wileyonlinelibrary.com]

between the two landforms (see Figure 5c). In short, the initial linear platform and outslope with benches were reconstructed to a surface which consists of a series of catchments with natural hillslope curvature and a constructed drainage line.

2.4 | Landform assessment method

The geomorphically designed landforms were assessed using the SIBERIA LEM. A description of the SIBERIA model follows below in Section 3. The SIBERIA modelling assessment of the 2020 geomorphic-based restorations (External waste rock dumps) was accomplished after the restoration was carried out, since it was not possible to undertake the calibration and characterisation at a pre-restoration time.

The outcomes will allow (a) undertaking soil erosion control, if needed, at the forecasted gullying location; (b) evaluating with ground truthing the fit between the erosion occurrence and the modelled gullying.

The two waste dumps restored in 2020 are termed EWRD and WWRD (Figure 5b). The EWRD and WWRD have areas of 3.25 and 1.82 ha respectively (Table 1). Both sites had steep average slopes.

The characteristics of the geomorphically reshaped WRD can be described as convex-concave scalloped hillslopes, either draining to zig-zag drainage lines (also part of the design) or blending with noses and hollows of the natural hillslopes on which the sidehill WRD recline. Both have mature hypsometric curves (described later) (Strahler, 1952, 1964) and conceptually should have a minimal sediment output as the landscape is already in maturity.

The subsoil and topsoil used for the restoration, as a cover over the waste material, were respectively carbonate colluvia and calcaric cambisols developed on the former landscape, with a depth of 30 cm. This material was obtained both from former surficial deposits and soils (removed by the mining activity, mixed with the wastes) and from the surrounding landscape. This material was well mixed with particle size analysis demonstrating this.

Due to the high erodibility of the materials, as demonstrated by the observed on-site erosion and derived LEM model parameters (described later in Section 3.2), an organic mat (erosion control blanket) was placed over the surface at high slope gradient (>40%) areas of the surface of the External waste dumps (Figure 5b). This erosion

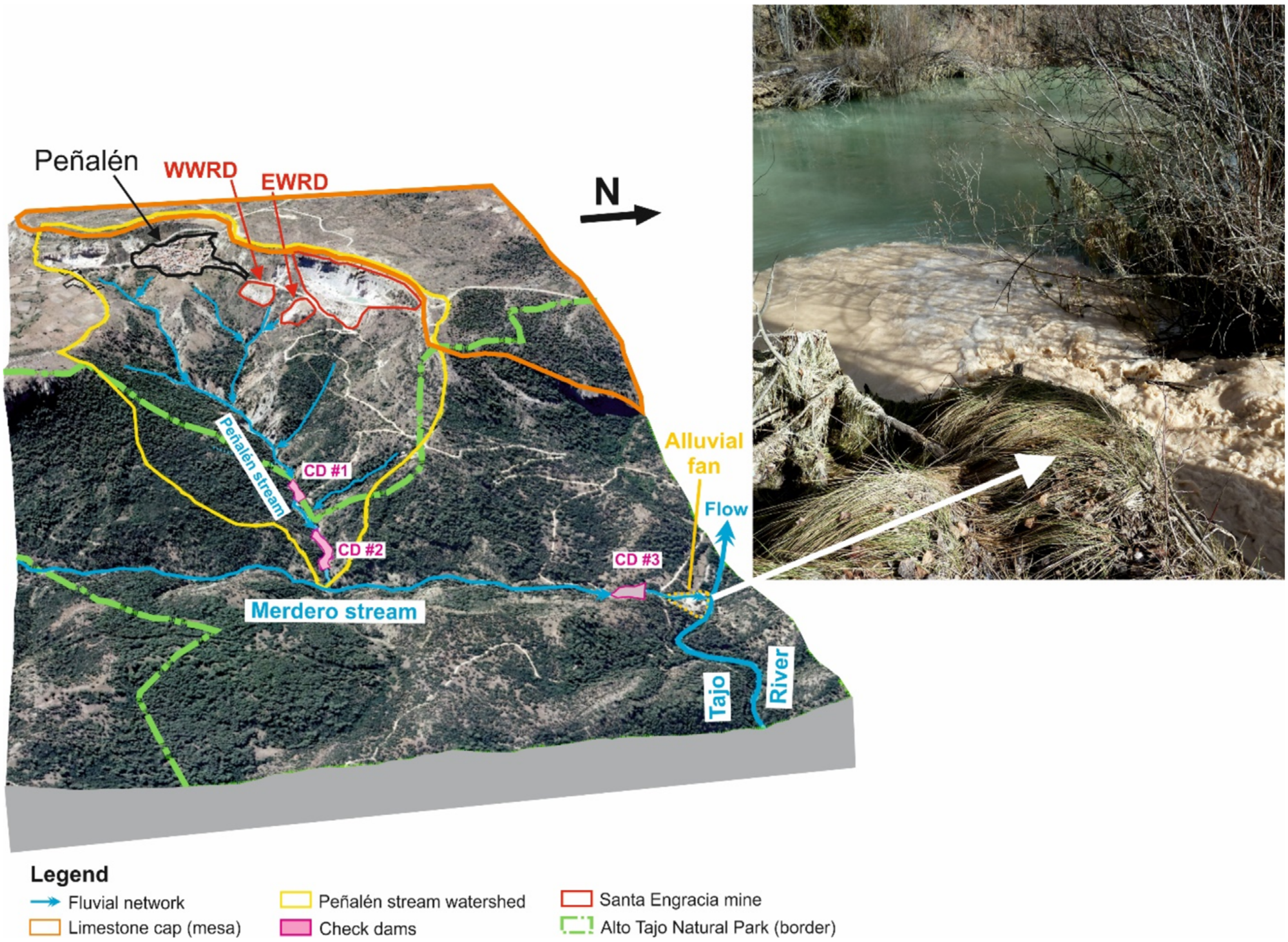


FIGURE 3 Geomorphic setting hydrologic connectivity framework of the Santa Engracia mine, showing the two waste rock dumps that are the focus of this paper (WWRD and EWRD). The mine is located at the head of the Peñalen stream watershed, at the border of a limestone capped mesa (altitude 1400 m asl). The surrounding landscape, outside the cap, is formed by canyon valley sides. Before the LIFE RIBERMINE project, erosion from this mine yielded sediments to the Peñalén stream. From this watershed, the sediments were delivered to the Merdero stream, already within the Alto Tajo Natural Park and finally delivered the Tajo River, again within the Alto Tajo Natural Park. The photo displays a typical event of high turbidity waters entering the Tajo River from the Merdero mouth. The altitude of this point is 1000 m asl. asl, above sea level; EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump. [Color figure can be viewed at wileyonlinelibrary.com]

control blanket (Fijavert HC350, https://www.projar.es/) was a mat which was 50% hay and 50% coconut fibre intertwined with photodegradable polypropylene meshes and threads. The blanket provides erosion protection until vegetation is established and then photodegrades and is incorporated into the soil. As discussed above for the External waste dumps, the landscape evolution and erosion modelling (SIBERIA) assessment used this landscape and surface as the starting point. Further details on material characteristics and hydrology are described in Sections 3.2 to 3.4.

3 | METHODS

The most commonly used model to predict soil erosion is the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Program (WEPP) (Wischmeier & Smith, 1978; https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/wepp/research/). They are well understood and proven to be accurate, reliable and continue to be very useful for many applications. They can be employed across a range of agricultural and other environments (Wischmeier & Smith, 1978; Evans & Loch, 1996; Evans, 2000; Hazelton & Murphy, 2007; Brooks et al., 2014; https://www.fs.usda.gov/ccrc/tools/watershed-erosion-prediction-project). Recently, more advanced catchment scale models based on the framework of the RUSLE have been developed, such as the SedNet model (Kinsey-Henderson et al., 2005; Wilkinson et al., 2008; Gibson and Hancock, 2020). These models are very useful predictive tools; however, these models do not predict deposition which constrain landscape evolution prediction.

3.1 | LEM

SIBERIA is a LEM that has been used extensively for erosion on post-mining landscapes by the mining industry, mostly in Australia, and was first used in the 1990s (Hancock et al., 2008; Hancock & Willgoose, 2018; Willgoose & Riley, 1998).

SIBERIA provides:

a. Visualisation of erosion and where it occurs (i.e. gullies, rills)
b. An erosion rate—both in t ha^{-1} year^{-1} and denudation (mm year^{-1}) (i.e. landscape lowering)

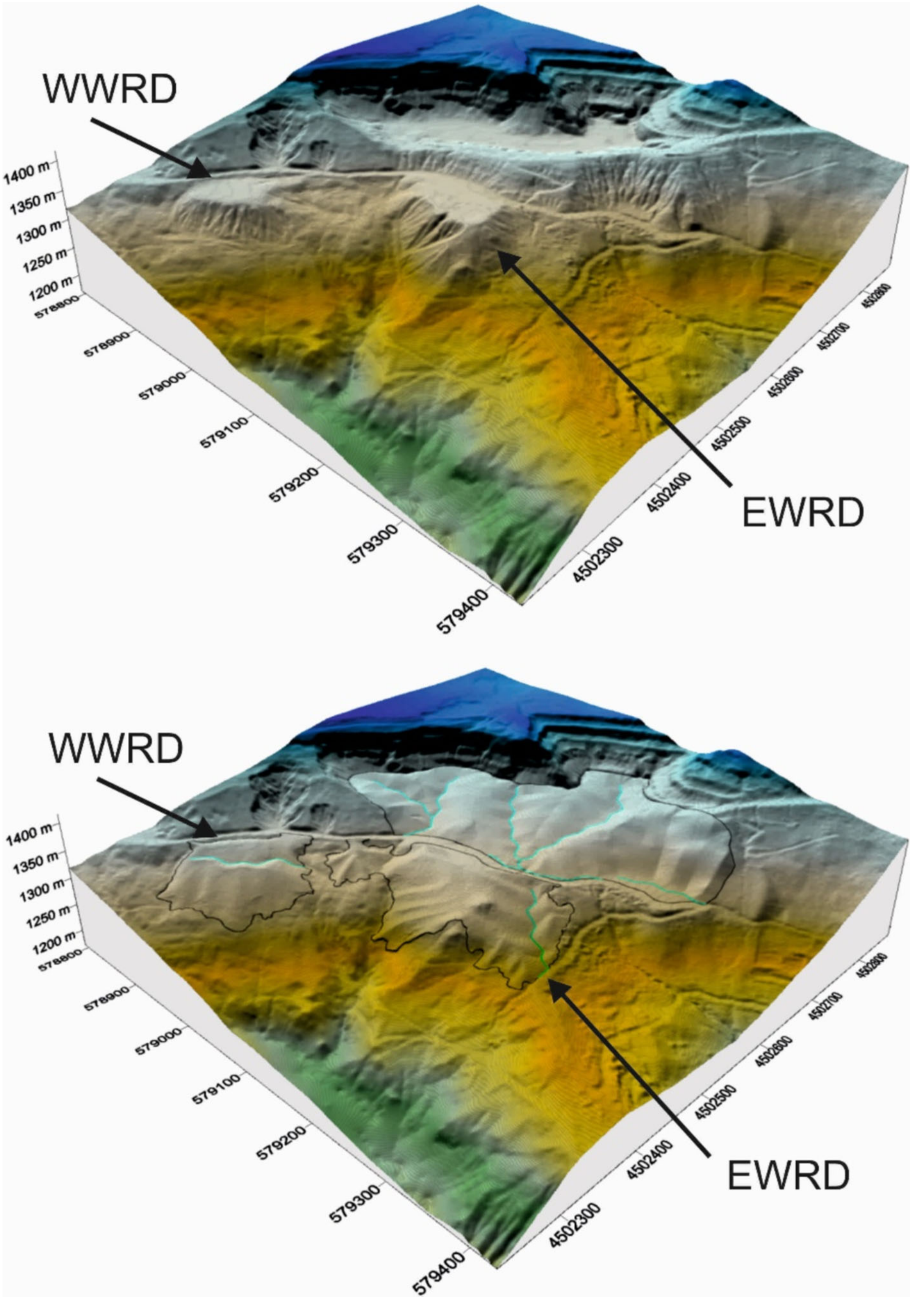


FIGURE 4 Top, pre-restoration topography of the Santa Engracia mine. Bottom, geomorphic landform restoration design, through GeoFluv-Natural Regrade, showing: (a) the limits of the designs (black line); (b) the main designed fluvial channels (blue lines). The external waste dumps (WWRD and EWRD) are the focus of this paper. EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump. [Color figure can be viewed at wileyonlinelibrary.com]

The model can be run at decadal through to millennial time scales. A summary of mine site application can be found in Hancock and Willgoose (2018).

The sediment transport equation of SIBERIA is.

$$q_s = q_{sf} + q_{sd} \tag{1}$$

where q_s (m^3/s/m width) is the sediment transport rate per unit width, q_{sf} is the fluvial sediment transport term and q_{sd} is the diffusive transport term (both $m^3\ s^{-1}\ m^{-1}$ width).

The fluvial sediment transport term (q_{sf}), based on the Einstein-Brown equation, models incision of the land surface and can be expressed as:

$$q_{sf} = \beta_1 q^{m_1} S^{n_1} \tag{2}$$

where q is the discharge per unit width (m^3/s/m width), S (m/m) is the slope in the steepest downslope direction and β_1, m_1 and n_1 are calibration parameters where m_1 and n_1 are dimensionless and β_1 is scaled for the DEM grid size (Willgoose, 2018).

The diffusive erosion or creep term, q_{sd}, is

$$q_{sd} = DS \tag{3}$$

where D ($m^3\ s^{-1}\ m^{-1}$ width) is diffusivity and S is slope. The diffusive term models smoothing of the land surface and combines the effects of creep and rainsplash.

SIBERIA does not directly model runoff (Q, m^3—for the area draining through a point). It relates discharge to area (A) draining through a point as

$$Q = \beta_3 A^{m_3} \tag{4}$$

where β_3 is the runoff rate constant and m_3 is the exponent of area, both of which require calibration for the particular field site.

The model is mostly run at annual time scales as it is more convenient to model the average effect of the above processes with

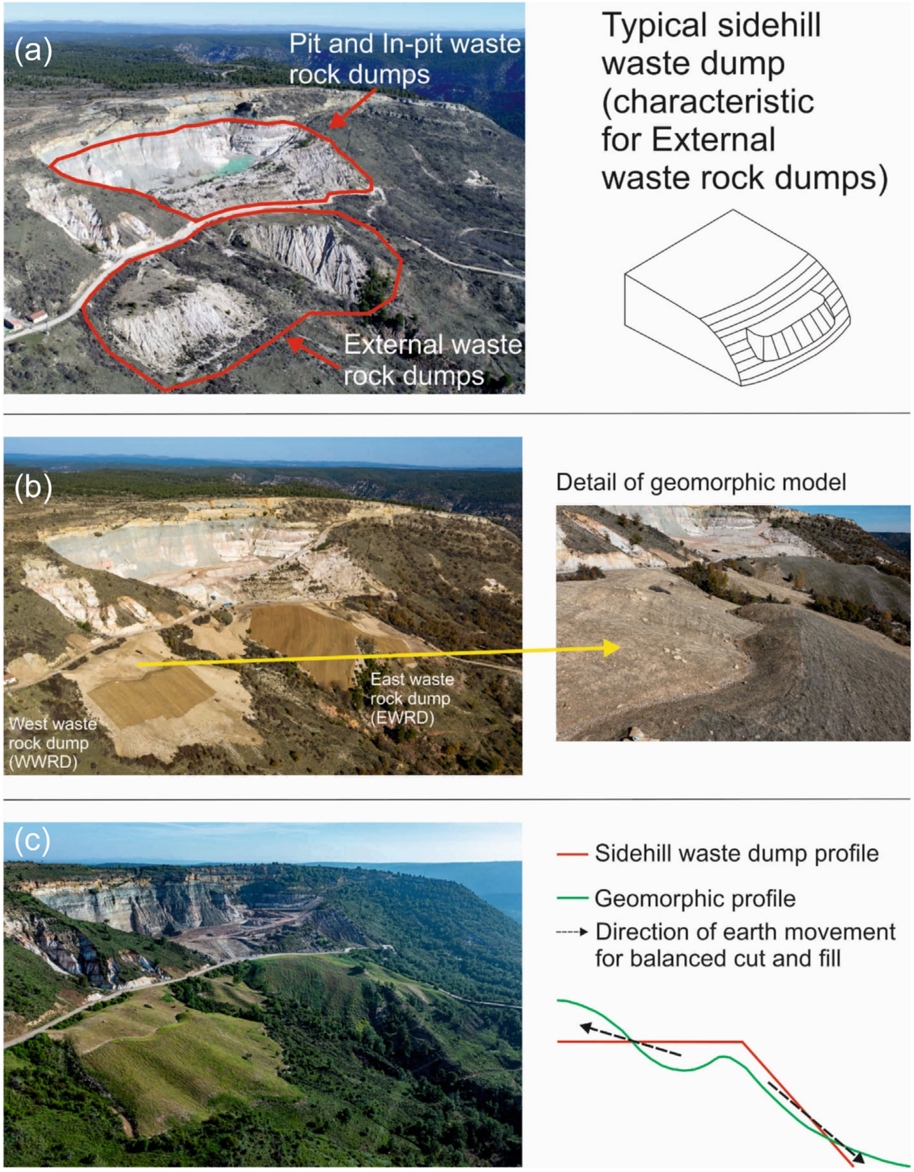


FIGURE 5 Santa Engracia mine. (a) Pre-restoration scenario (March 2020, image by DIEDRO); notice the generalised gullying-badland topography, indicator of severe erosion and the typical sidehill morphology at the external waste rock dumps (scheme redrawn from Orman et al., 2011). (b) Postgeomorphic regrading, topsoil cover, organic mat and seeding (November 2020); detail of the transverse valley at the right. (c) Situation after vegetation germination at the external waste rock dumps (May 2021); notice the scalloped long hillslope; to the right, comparison of the sidehill waste dump profile with the geomorphic one, showing direction of earth movement for balanced cut and fill; (b, c) images by Fotolanga. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Site characteristics for the geomorphically constructed landscapes at the external waste rock dumps.

	WWRD	EWRD
area	1.82 ha	3.25 ha
relief	48 m	47 m
average slope	37%	36%

Abbreviations: EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump.

parameters determined for annual time steps. Hence, SIBERIA does not model an individual large storm. SIBERIA therefore describes how the catchment is at any given time based on the parameter inputs at annual time steps. Landscape input is in the form of a DEM, which is used for determination of drainage areas and slope and in response to erosion and deposition adjusts each elevation in the DEM grid.

The SIBERIA LEM has been widely employed for erosion assessment for a range of postmining landforms (Hancock et al., 2000, 2008; Hancock & Turley, 2005; Hancock & Willgoose, 2018). A detailed description of SIBERIA can be found in Willgoose et al. (1991a) and Willgoose (2018). Further detail of how and where SIBERIA has been used is available in Hancock and Willgoose (2018).

Like all models, before SIBERIA can be used, parameters and their calibration for the sediment transport equation (Equation 2) and area-discharge relationship (Equation 4) are required. The fluvial sediment transport equation (Equation 2) in SIBERIA is parameterised using input from sediment transport and hydrology data. This parameterisation process is described in detail by Evans et al. (2000), Evans et al. (2000) and Hancock et al. (2000). This process can use field data collected from rainfall/runoff plots or laboratory flume and/or rainfall simulator data (Evans et al., 2000; Hancock et al., 2002; Hancock et al., 2007; Hancock et al., 2021; Welivitiya et al., 2021).

3.2 | Parameters—Soil

SIBERIA input parameters can be generic, based on an understanding of the local materials (i.e. soil texture) and climate, or site specific. The most reliable use of the model occurs with site-specific parameters.

TABLE 2 Parameters employed for the SIBERIA modelling for the Santa Engracia mine. The high erosion parameters represent a bare surface, while the organic mat parameters represent the surface covered with an erosion resistant fabric. The postorganic mat parameters are an estimation of the effect of organic mat breakdown but with vegetation cover reducing erosion.

	High erosion	Organic mat	Postorganic mat
β_1	0.02	0.001	0.002
m_1	2.0	1.2	2.0
n_1	2.1	2.1	2.1
β_3	1	1	1
m_3	1	1	1

Calibration at the Santa Engracia site has been based on erosion development on similar materials at the nearby Nuria mine (Zapico et al., 2020). At this site, the surface is constructed of fine silica sand with local subsoil (carbonatic colluvia) and topsoil added and then revegetated. The material at Nuria has a very similar soil texture to that of materials at Santa Engracia (Martín-Moreno et al., 2018; Zapico et al., 2020). This material translates to parameters that can be used at the site, based on soil texture (here a loamy sand) (Table 2).

In the SIBERIA sediment transport equation, the parameters m_1 and n_1 (Equation 2) control the form of erosion. The values of m_1 and n_1 vary widely but for most landscapes and they both range between 1 and 3 (Kirkby, 1971; Welivitiya et al., 2016; Willgoose & Riley, 1998; Willgoose & Sharmeen, 2006).

High-resolution images were captured at completion of the restoration earthworks in August 2015 and then again in November 2017 at the Nuria site (Zapico et al., 2020). Digital photogrammetry was used to produce high-resolution (0.2 m) regular grid DEMs of the site. Given the similarities in climate, physiographic conditions and materials, this data was used to calibrate SIBERIA.

At the Nuria site, the DEM in November 2017 demonstrated some gullying. This initially suggested parameters of $m_1 > 1.5$ and $n_1 > 1.5$ (Kirkby, 1971). Using the initial landscape as the starting conditions and parameters of $m_1 = 1.5$ and $n_1 = 1.5$, these parameters were adjusted until a best match was found with the November 2017 photogrammetric data and the model prediction. This process found that values of $m_1 = 2.0$ and $n_1 = 2.1$ provided the best match to gullies measured from the photogrammetric data. These values are within the range of values for fluvial process dominated catchments suggested by Kirkby (1971) assuming a spatially uniform sediment production rate. A sensitivity study of the parameters was conducted by elevating and reducing m_1 and n_1 by units of 0.1 which confirmed the most appropriate set as described above. Therefore, the parameters are what could be reasonably expected for the site and materials examined here.

Soil erodibility (β_1) is recognised to be well-described by the RUSLE K factor which can be determined from the material particle size distribution (Evans & Loch, 1996; Hazelton & Murphy, 2007; Sheridan et al., 2000). Here, particle size distribution from site data (Zapico et al., 2020) was used. Using the soil particle size classification and K factor (soil erodibility; Wischmeier & Smith, 1978) table of Hazelton and Murphy (2007), the material can be classified as a sandy loam with little rock content to reduce erosion, to which we have assigned a K factor of 0.02. This K factor can be input into the SIBERIA model assuming the surface has an absence of vegetation (Willgoose, 2012).

For many sites where there is bare earth or where the site has been degraded with little or no vegetation (i.e. mine sites with a bare nonvegetated surface or a surface with vegetation removed by fire—discussed later), this erodibility (K) value can be used directly in the model. However, many sites have a rock cover or armour. In the case here, a vegetation cover should be present after 3 years post-rehabilitation. Similar to the RUSLE K factor, the RUSLE C (Wischmeier & Smith, 1978) factor can be used to determine the expected erosion reduction due to vegetation. There is considerable data on the role of vegetation, and a C factor can be directly determined from tables (Blanco & Lal, 2008; Wischmeier & Smith, 1978) from a variety of sources. Here, we use a C value of 0.01, which represents an established grass cover. The authors have employed this approach for a site with similar soil and rainfall (Blanco & Lal, 2008; Hancock & Wells, 2020). The SIBERIA β_1 value is then determined by multiplying the K value by the C value (0.001) (Table 2). Bulk density used here was 1.5 t m^{-3}.

3.3 | Parameters—Organic mat

Given the high erodibility of the surface material, alternative methods for erosion control were examined. Here, an organic mat or erosion blanket (incorporating topsoil and seeding) was employed to reduce erosion, covering some parts (those with highest gradient) of the restored waste dumps (Figure 5b). The remaining surface was spread with topsoil and seeded. The organic mat provides protection from sheetwash, rill and gully erosion. The mat should provide protection for several years (assumed here to be 3 years). However, it is recognised that over time, the material will degrade with erosion protection subsequently being provided by vegetation. There are no parameters available for an erosion blanket, and here, we assume parameters of $m_1 = 1.2$ and $n_1 = 2.1$ given that slope is consistent across all landscapes, and with the erosion blanket, it is unlikely that gullying and riling will occur with such a surface cover. These values represent a surface that will be dominated by sheetwash as the blanket will protect the surface from riling and gullying (Kirkby, 1971). A β_1 value of 0.001 (equivalent to a dense and erosion resistant grass cover) was used here to represent the erodibility of a surface covered in a dense organic mat (Table 2). This value could be considered conservative (a high value) as the organic mat provides a continuous cover which, when combined with vegetation would likely reduce erodibility further.

These were named 'organic mat' parameters. The organic mat covered a substantial proportion of both the EWRD and WWRD. Here, for modelling simplicity, we have employed these parameters across the whole surface. This provides a best-case scenario.

3.4 | Parameters—Postorganic mat

The organic mat is a short-term surface stabilisation material that slowly degrades with vegetation assumed to provide erosional stability over the long-term. Here, we assume that the organic mat will last for a maximum of 3 years before it is degraded. The surface will then consist of topsoil but with the erosion rate reduced by the vegetation cover, which will be assumed homogeneous across the site. Here, a set of parameters was employed (named postorganic mat) with a reduced β_1 value representing a good vegetation cover but with the same discharge and slope exponents for high erodibility material (Table 2). This is the most realistic field-based scenario that is considered likely for the site and provides one potential evolutionary outcome.

3.5 | Landscape and DEM data

The site was constructed before modelling, and topography was obtained by structure from motion photogrammetry combined with an unmanned aerial vehicle (SfM-UAV) technique (Figure 4). The photos were surveyed on 15th October 2020, by a DJI Phantom 4 Pro drone. 905 80% overlapping photographs were collected with programmed flights from both zenithal and oblique angles. The UAV was kept at a constant altitude with a 112-m height above the ground to ensure a ground resolution of 3.06 cm pix^{-1}. Fifteen fixed targets were placed over the area as ground control points (Figure 6). The area covered by the photos ensured that a survey area well outside the catchment boundaries was captured. Their coordinates were measured with a differential Leica 1200 GPS. Photos and ground control points were processed with Agisoft PhotoScan software. The final registration error (RMSE in cm) was *x*: 6.6; *y*: 7; and *z*: 2. The point cloud density was 266 points m^{-2} (Figure 6).

This data was then gridded using kriging to a regular grid spacing of 0.5 m with the EWRD and WWRD extracted using catchment delineation software from this data (Figure 7). A DEM grid size of 0.5 m was more than sufficient to capture landscape shape and hillslope curvature as well as considered sufficient to capture erosion features such as small gullies, if already present.

All SIBERIA simulations used these landscapes as the starting surface.

4 | MODEL SETUP

The SIBERIA model was run using the parameters described above (Table 2). The model was run for the entire landscapes with sediment free to leave from the DEM boundaries (Figure 7).

The simulations performed here were as follows:

1. High erosion and organic mat simulations for 100 years. The former is a worst case scenario, and the latter represents an ideal theoretical situation with minimum potential erosion.
2. The organic mat parameters were run for 3 years then restarted at year 4 with postorganic mat parameters. A 3-year period represents an initial low erosion rate and allows drainage lines to form. The model run was then continued for 100 years with postorganic mat parameters. As discussed above, we consider that this is the most realistic scenario to occur.

The site was restored using terraces in 1990 which then evolved to badlands up to 2020 (time span of 30 years), before this restoration project started (see Figure 1). All modelling was therefore continued for a length of 100 years as it is considered to be within a human

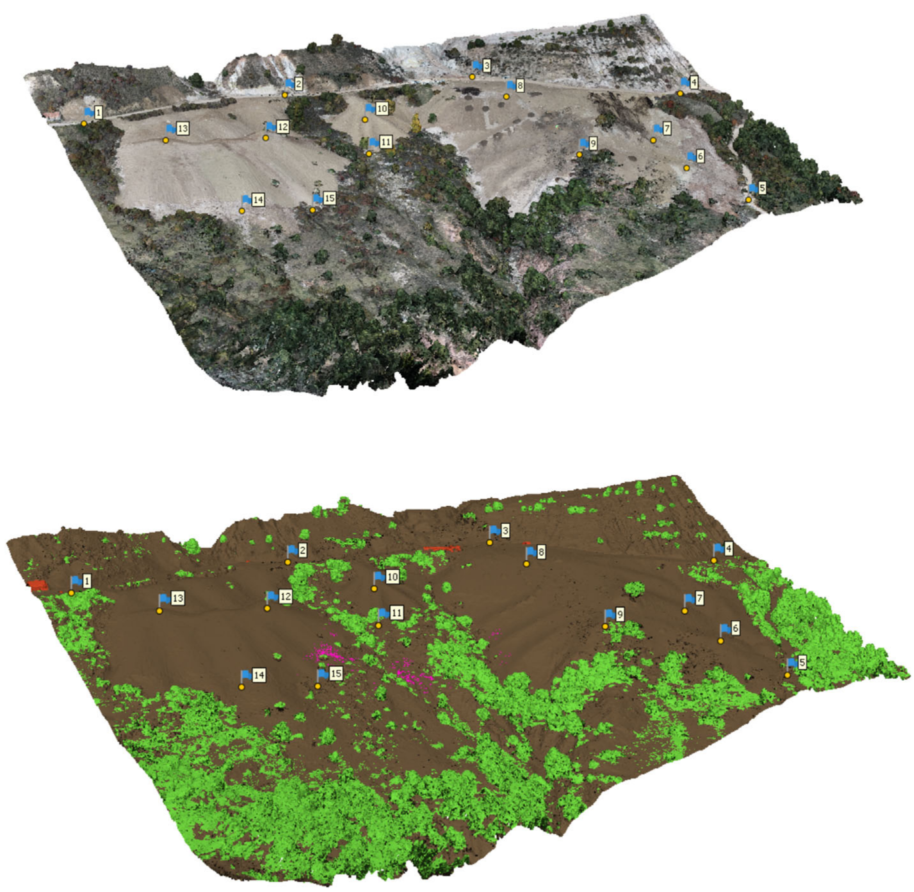


FIGURE 6 View of the dense point cloud for the external waste dumps, classified (brown, ground; green vegetation; pink, noise) for the reconstructed hillslopes. [Color figure can be viewed at wileyonlinelibrary.com]

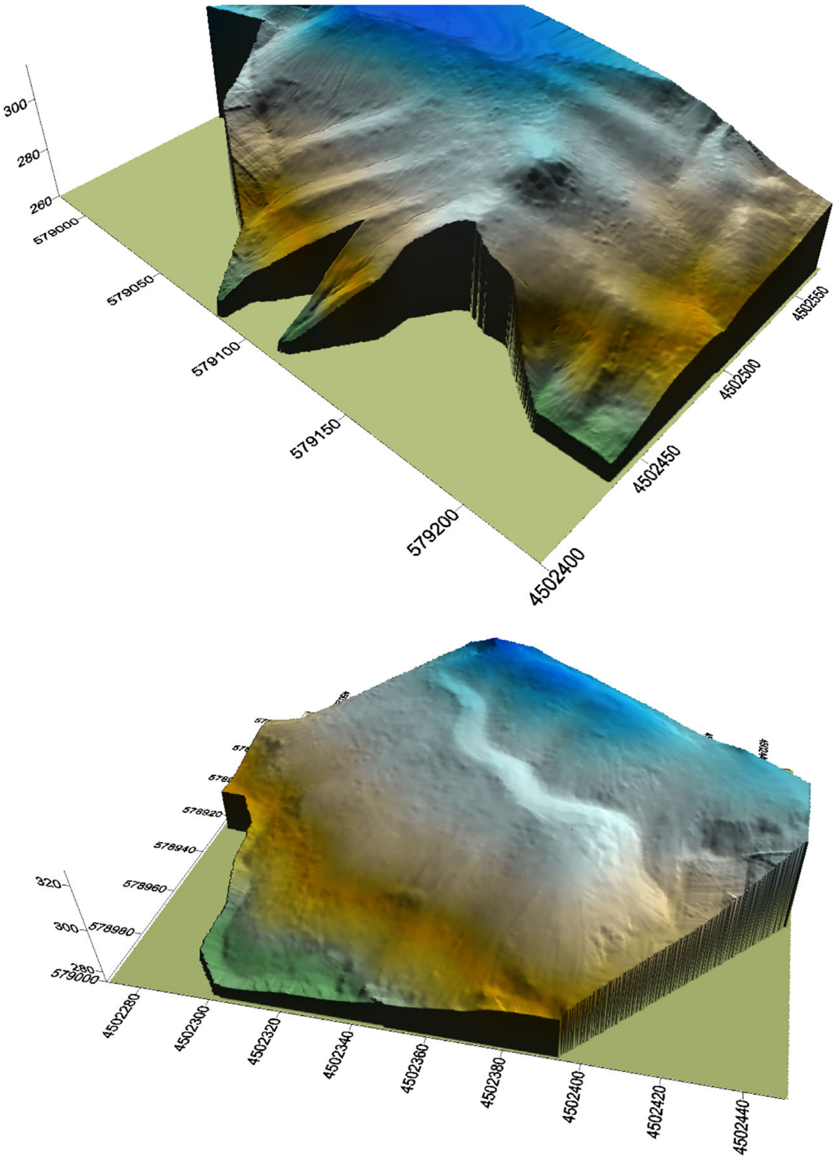


FIGURE 7 External East Waste Rock Dump (top) and External West Waste Rock Dump (bottom). All dimensions are metres. *Z* values are 'above 1000 m asl'. [Color figure can be viewed at wileyonlinelibrary.com]

management time frame (given the information available over the referred 30-year period). This 100-year period, while not geomorphic time, allows any landscape design strengths and weaknesses to be identified. It also represents the period of most rapid development of a new landform.

Erosion and deposition patterns were determined by differencing the year zero DEM from the years 10, 50 and 100 modelled elevations. This approach also allows maximum depth of erosion (in this case gully depth) as well as depth of deposition to be determined.

5 | RESULTS

5.1 | Geomorphic landform characteristics

The landforms were designed using a geomorphic approach (GeoFluv–Natural Regrade) which optimised hillslope length, slope and curvature to reduce both erosion as well as provide a more natural and visually appealing landscape which integrates with the surrounds (Figures 5–7). Such landforms have a series of subcatchments with defined drainage lines. In particular, the WWRD was dominated by a transverse catchment as its major landscape feature, with a scalloped hillslope starting from a low divide of the catchment (see description of this model in Figure 5). The EWRD consisted of a longitudinal catchment to the east and a main scalloped hillslope to the west.

The constructed landscapes were assessed for their geomorphic characteristics using the hypsometric curve and the area-slope relationship. The hypsometric curve (Langbein, 1947) is a nondimensional area-elevation expression providing a comparison of catchment morphology with different areas and elevation. The hypsometric curve has been generally used as an indicator of the catchment geomorphological maturity with landforms divided into youthful, mature and old characteristic shapes, reflecting increasing catchment age (Strahler, 1952, 1964).

Examining the two largest catchments from the EWRD demonstrates that the landscape has a catchment with a youthful and mature hypsometric form as classified by hypsometry (Flint, 1974; Strahler, 1952, 1964) (Figure 8). The WWRD has a mature landscape form.

Catchment geomorphology can also be assessed using the area–slope relationship. The area–slope relationship, which is the

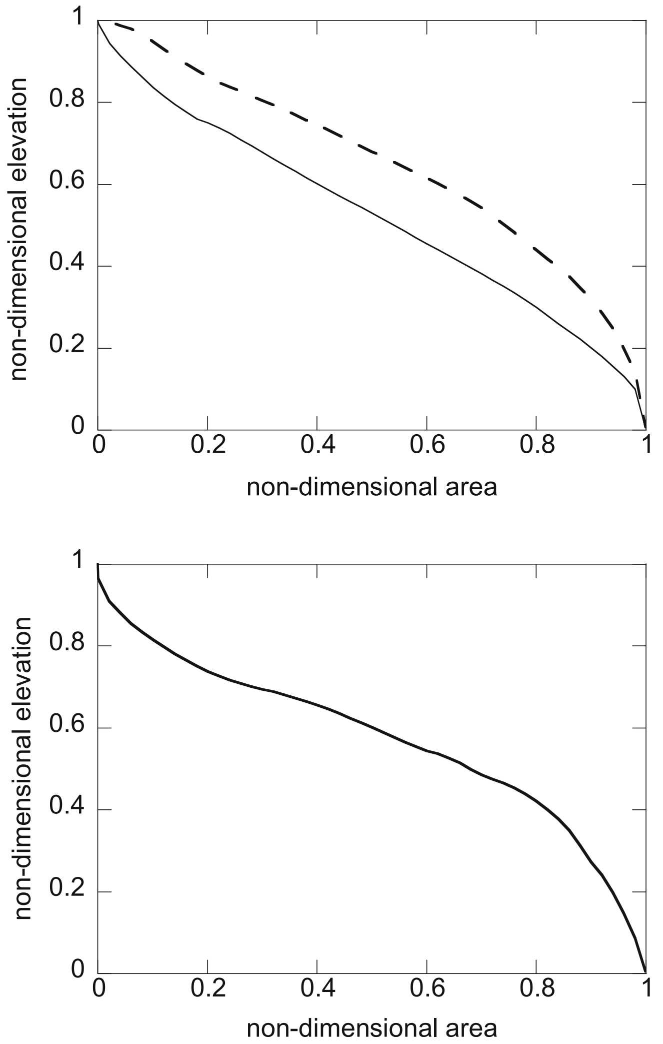


FIGURE 8 Hypsometric curves for EWRD (top) and WWRD (bottom) geomorphically reconstructed landscapes. Due to the complexity of the EWRD, the landscape hypsometric curves were determined for the two largest subcatchments hence the solid and dotted lines. The curves represent landscapes that are at or near a mature form similar to catchments that have evolved via natural fluvial processes rather than being constructed as in this study. EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump.

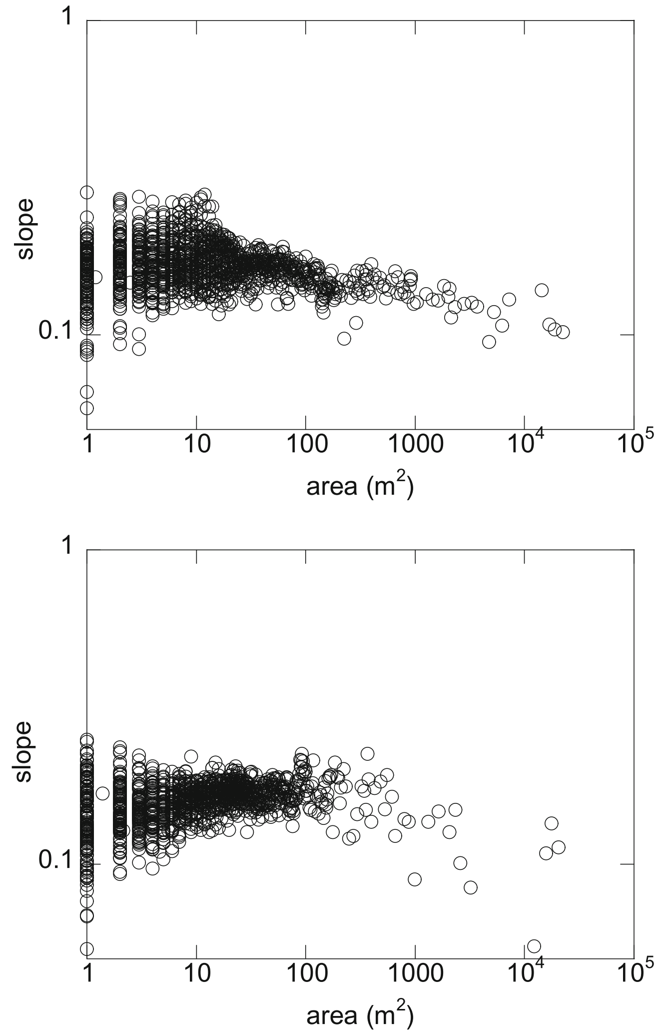


FIGURE 9 Area-slope relationship for EWRD (top) and WWRD (bottom) geomorphically reconstructed landscapes. The data represents landscapes which have evolved via similar diffusive and fluvial processes as that of natural processes. EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump.

relationship between upslope area draining through a point versus the slope at that point, provides geomorphic information useful for calibration (Langbein, 1947; Strahler, 1952, 1964; Willgoose, 1994) (Figure 9). A mature catchment that has a hillslope evolved by both diffusive and fluvial erosion processes will have a log–log positive area at small areas, which represents that part of the hillslope dominated by diffusive processes, and as area increases a log–log negative relationship, which represents that part of the catchment dominated by fluvial processes (Willgoose, 1994, 2018). Both analysis demonstrate a landscape that has both diffusive and fluvial regions with the diffusive region extending from approximately 100 m^2 for both the EWRD and WWRD. Overall, given the form of the hypsometric curve and area–slope relationship, the designed landscapes could be considered to have a form similar to that of natural young to mature catchments that have both diffusion and fluvial erosion dominated regions.

5.2 | Erosion results

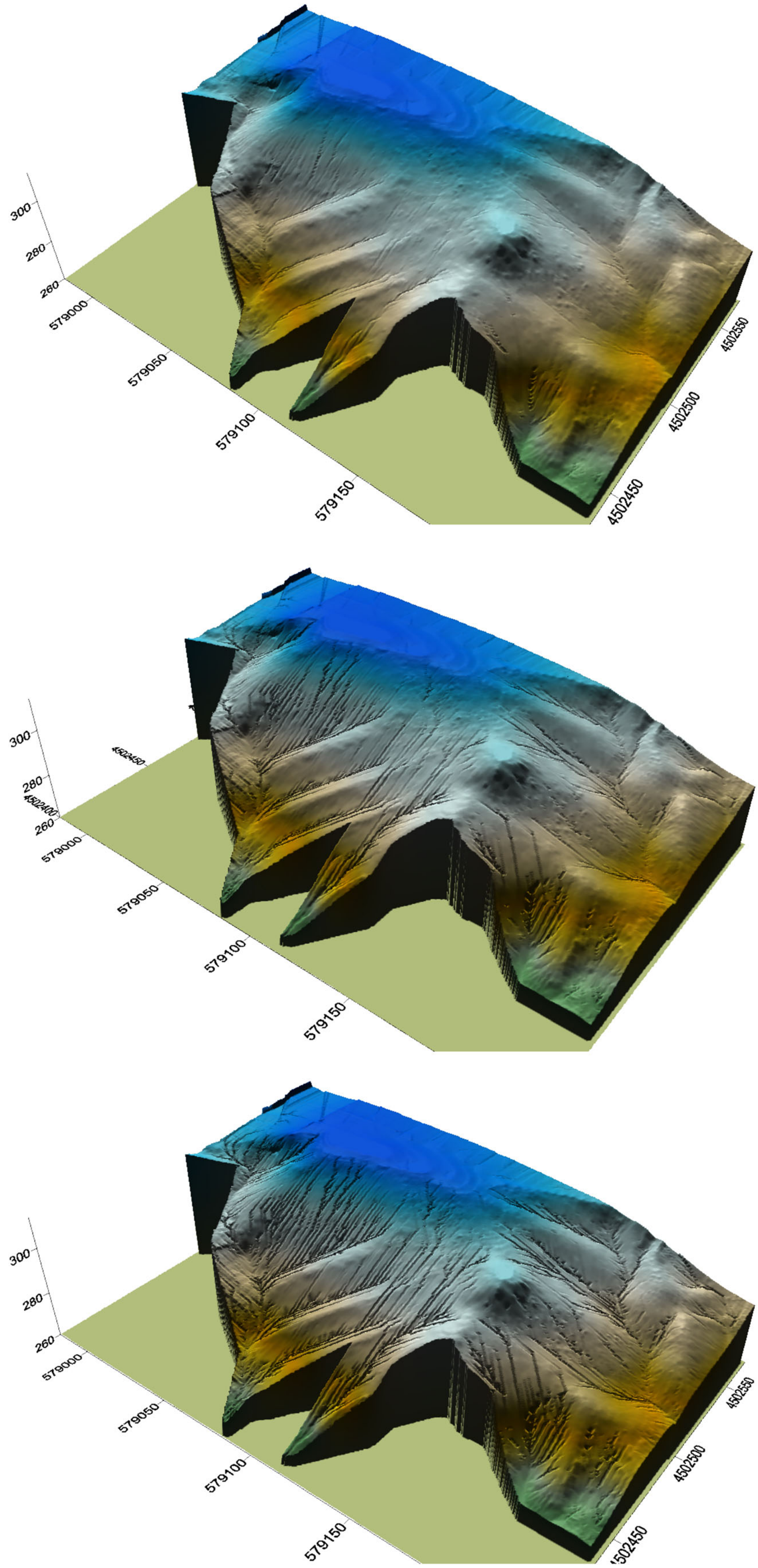
5.2.1 | High erosion

The modelling assumes a constant set of high erosion parameters for the 100-year period. Using the high erosion parameters, gullies occur on both the external slopes of the EWRD and WWRD (Figures 10 and 11).

At 10 years, there are small gullies forming on the reconstructed hillslopes as well as the channels. These gullies are discontinuous. These gullies grow with time such that the entire reconstructed hillslopes have a series of discontinuous gullies at 50 years. At 100 years, the landscape demonstrates a network of both continuous and discontinuous gullies.

Of note here is that both the hillslopes and channels are prone to gullying. The erosion rates are similar for both landscapes (~14 t ha^{-1} $year^{-1}$) (Table 3). However, this value is an average over the entire modelled landscape domain. Erosion rates in the gully areas are likely to be several times higher.

FIGURE 10 East waste rock dump initial landscape initial surface at 10 (top), 50 (middle) and 100 years (bottom) using high erosion parameters. All dimensions are metres. [Color figure can be viewed at wileyonlinelibrary.com]



5.2.2 | Organic mat

The modelling assumes a constant and stable organic mat cover for the 100-year period. Using organic mat parameters, there is little erosion (Figure 12). It is hard to discern any visible rilling or gullying. Erosion occurs by sheetwash.

For the WWRD, maximum depth of erosion at 100 years is 0.36 m with an average erosion rate of 1.3 t ha^{-1} year^{-1} (Table 3).

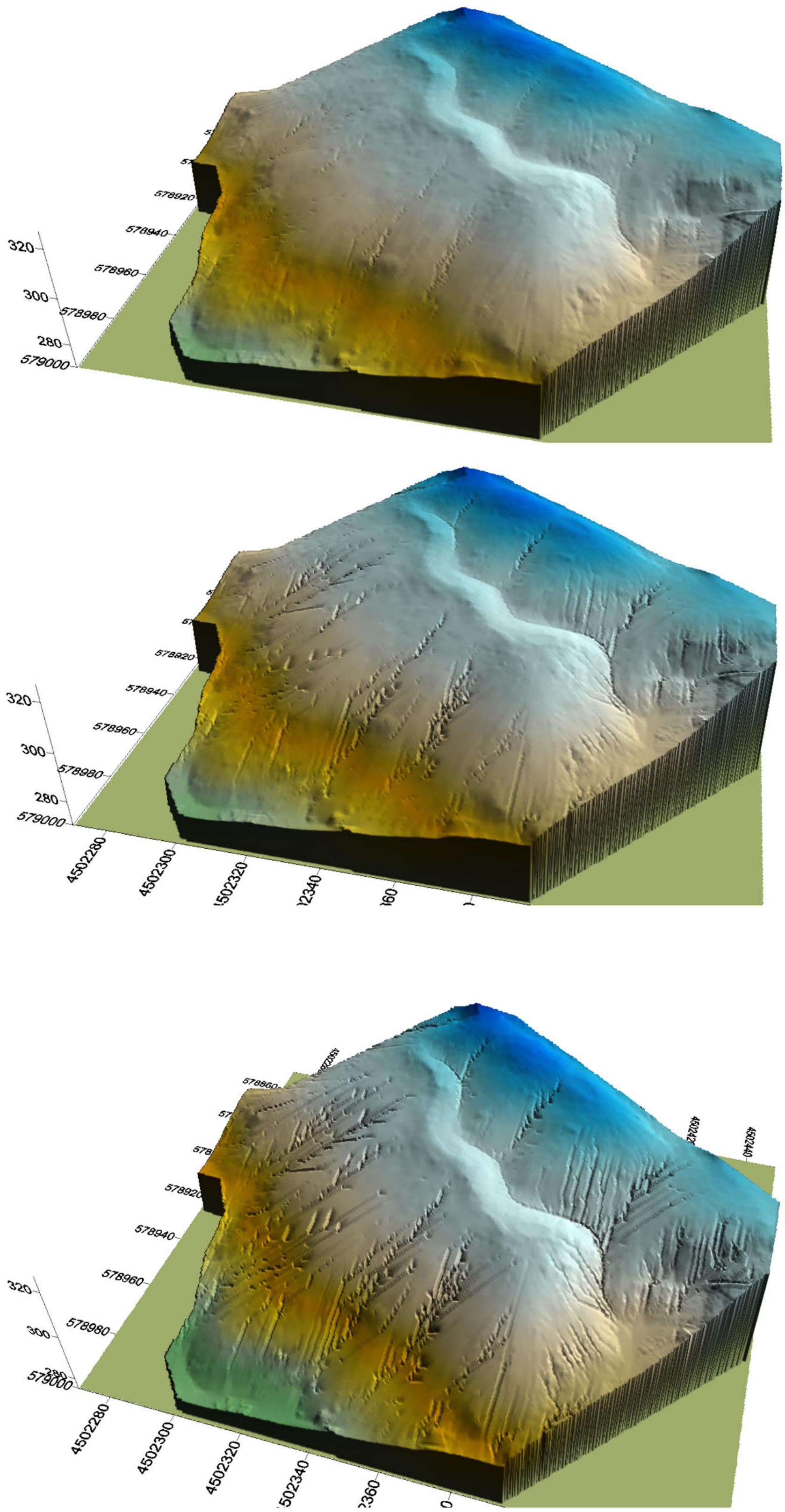


FIGURE 11 West waste rock dump initial landscape at 10 (top), 50 (middle) and 100 years (bottom) using high erosion parameters. All dimensions are metres. [Color figure can be viewed at wileyonlinelibrary.com]

Maximum erosion depth for the EWRD is 0.82 m at 100 years with an erosion rate of 1.2 t ha^{-1} year^{-1}.

5.2.3 | Postorganic mat

This assessment used organic mat parameters for 3 years then used the high erodibility parameters for the following 100 years (Figures 13 and 14). The results demonstrate that at 10 years, there is minor gullying for both the EWRD and WWRD (Table 3). Post 10 years, gullies begin to form and are quite visible at 50 years with both hillslope and channel having gullies present. This gullies continue to grow with time.

The erosion rate is relatively low (~6 t ha^{-1} year^{-1}); however, at 100 years, the gullies are over 2 m deep for both landscapes.

TABLE 3 Erosion rate and maximum depth and minimum depth (deposition) for the external waste rock dumps.

	EWRD			WWRD		
	10 years	50 years	100 years	10 years	50 years	100 years
	High erosion			High erosion		
Erosion rate (t ha^{-1} year^{-1})	16.5	15.0	16.5	14.2	14.0	14.1
Max. erosion depth (m)	0.78	2.61	0.78	0.71	1.17	3.4
	Organic mat			Organic mat		
Erosion rate (t ha^{-1} year^{-1})	1.5	1.4	1.3	1.6	1.5	1.2
Max. erosion depth (m)	0.15	0.25	0.36	0.32	0.65	0.82
	Postorganic mat			Postorganic mat		
Erosion rate (t ha^{-1} year^{-1})	5.0	5.1	5.25	5.25	5.9	6.3
Max. erosion depth (m)	0.42	1.75	2.1	0.78	2.02	2.7

Abbreviations: EWRD, East Waste Rock Dump; WWRD, West Waste Rock Dump.

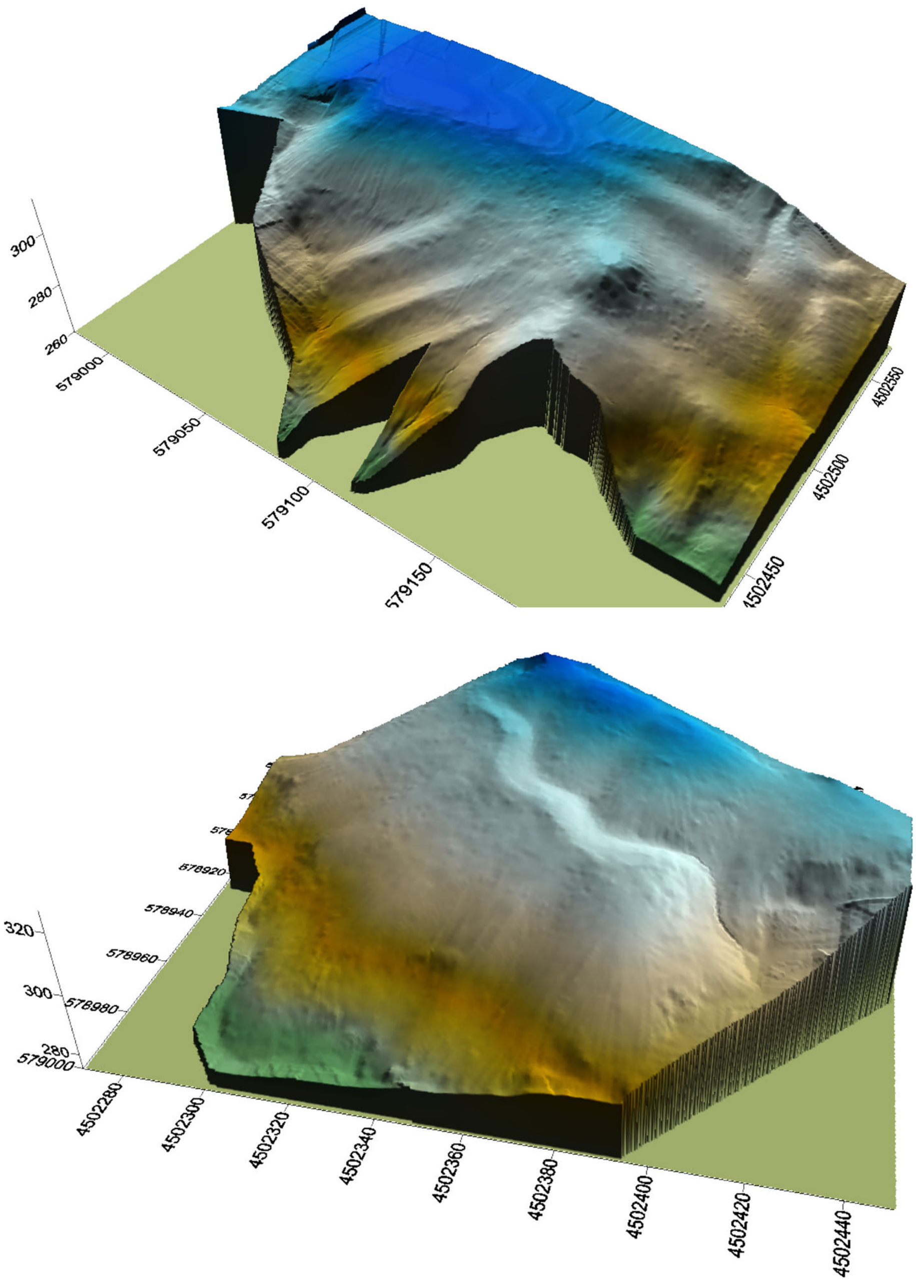


FIGURE 12 West waste rock dump (top) and east waste rock dump (bottom) at 100 years using organic mat parameters. [Color figure can be viewed at wileyonlinelibrary.com]

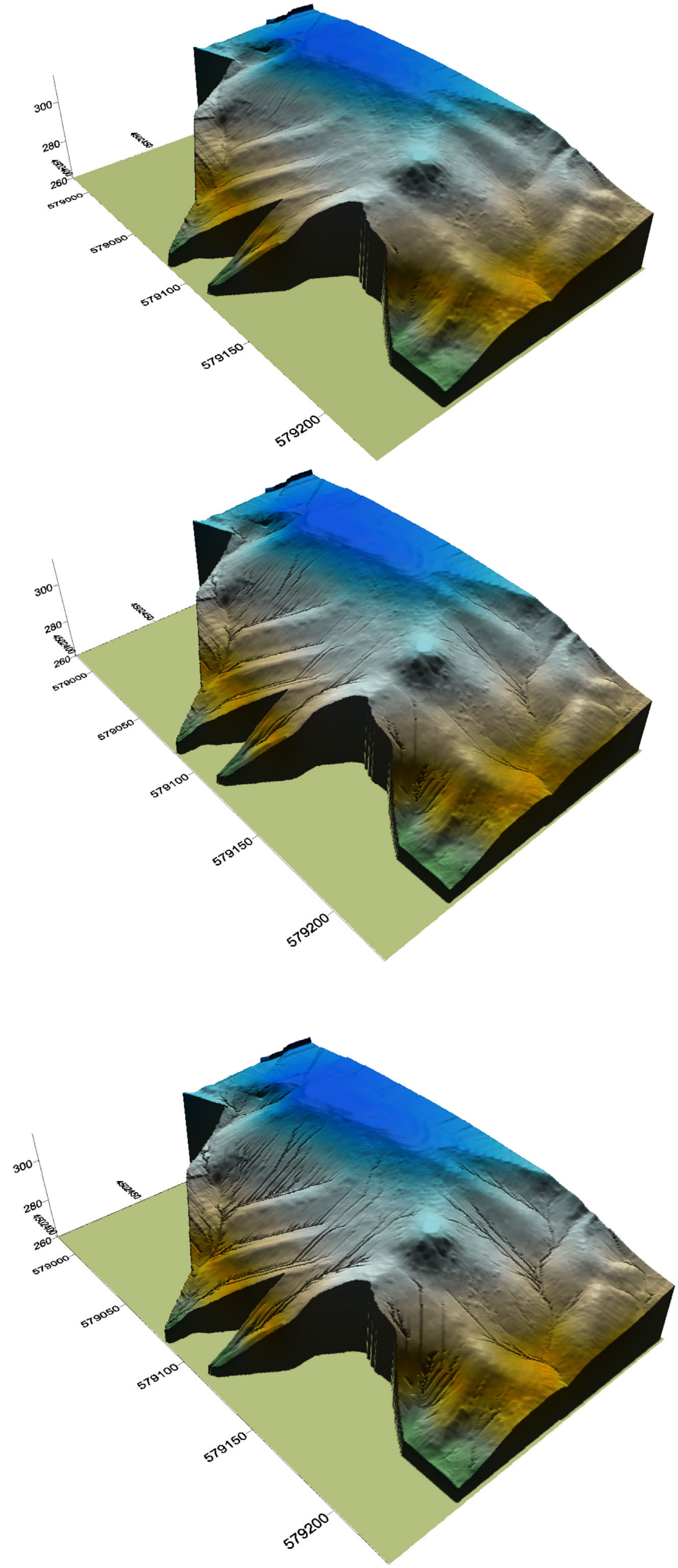


FIGURE 13 East waste rock dump at 10 (top), 50 (middle) and 100 years (bottom) using postorganic mat parameters. [Color figure can be viewed at wileyonlinelibrary.com]

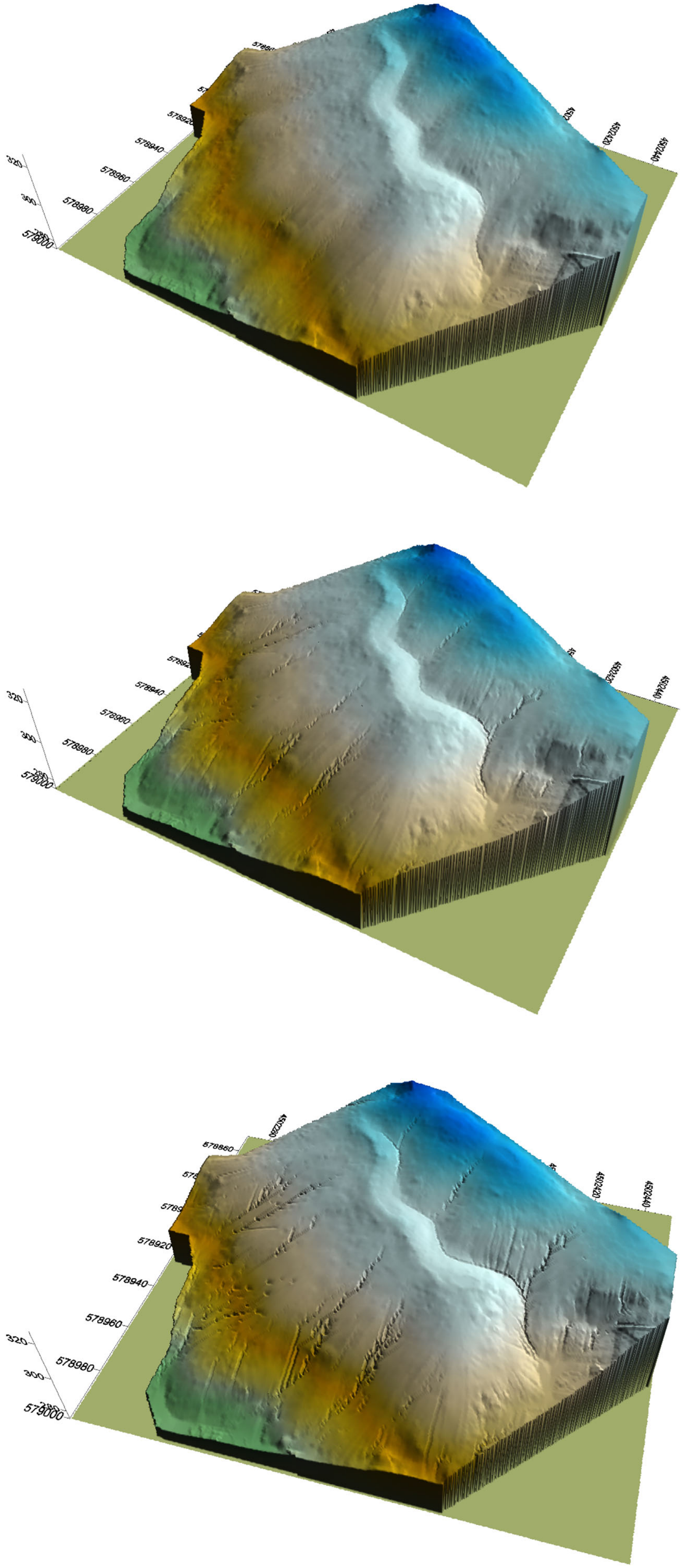


FIGURE 14 West waste rock dump at 10 (top), 50 (middle) and 100 years (bottom) using postorganic mat parameters. [Color figure can be viewed at wileyonlinelibrary.com]

6 | DISCUSSION

Any postmining landscape should be considered with the knowledge that it will exist for millennia and be subject to the forces of climate and resultant evolution. Therefore, it is important that any landscape be designed and constructed to be functional over millennial time scales. Understanding geomorphology and employing the latest tools are important to ensure that a design is optimised to become a functional integrated entity that optimally engages with the nonmined surrounds (Hannan, 1984; Shobe et al., 2024; Welivitiya & Hancock, 2024).

The design approach described here aims to emulate geomorphic landforms based on an understanding of the surrounding landscape, the surface materials and climate. For all sites, there are design constraints such as mine lease boundaries, infrastructure such as roads and power lines as well as physical features such as watercourses. In the case here, steep gradients, existing unpaved roads and mine highwalls provide added complexity. Therefore, any design will be a compromise between what is ideal and what is possible to construct within the framework of a geomorphically optimised design.

The only methods to evaluate a proposed design is (a) monitor the constructed landform over time or (b) model the proposed landscape assuming a series of surface conditions. Modelling geomorphic landform solutions at the design phase is the ideal situation. In the case described here, the modelling will allow (a) soil erosion control, if needed, at the forecasted gullying location; (b) evaluating with ground truthing the fit between the erosion occurrence and the modelled gullying.

Overall, the design process (see Figure 4) produced landscapes that have youthful to mature hypsometric curves as well as accompanying area-slope properties similar to surrounding natural catchments. The geomorphic design method employed provides both a more erosion resistant landform and promotes ecological diversity by creating different niches together with a landscape that visually blends with its surrounds. The method has been applied at other sites in Spain (Martín Duque, Tejedor, et al., 2021a; Martín Duque, Zapico, et al., 2021b; Zapico et al., 2018, 2020). This design process using the GeoFluv method and assessment using a LEM such as SIBERIA is here, for the first time, being employed in Europe. The method provides a template for the design and assessment of other sites degraded by human earth movements.

6.1 | Erosion characteristics

The WWRD and EWRD both have similar forms of erosion, erosion location and erosion rate. Using the high erosion parameters demonstrates that the entire landscape, both hillslope and channel, is at risk of gully erosion without protection from the organic mat and or vegetation. Employing an erosion mat or consistent vegetation cover stabilises the surface, and risk of erosion is reduced. However, there are likely to be areas where the erosion mat will be perforated, leading to concentrated flows and gullying. The main channels are risk areas and even with an erosion blanket/mat and good and continuous vegetation cover, localised gullying will occur. Practically, the erosion mat only covers the high slope and high risk areas.

There is also the question of the longevity and effectiveness of the organic mat and how vegetation stabilises the surface once the blanket has degraded. These simulations used the same set of parameters for both landforms. Employing postorganic mat parameters demonstrates that the landscapes are largely stable, with low erosion rates comparable to the Alto Tajo natural environment. The maximum rates, for 100 years (see Table 3), are 5.25 and 6.3 t ha^{-1} $year^{-1}$ for the EWRD and WWRD respectively. Given that the erosion rate for this landscape, before restoration, was 353 t ha^{-1} $year^{-1}$, this is a very positive outcome. Post 10 years, gullies begin to form on both the hillslope and channel for all sites. Therefore, amelioration work may be needed at 10 years, such as further application of additional organic mat, or channel armouring, at areas where gullies have formed.

The predicted erosion rates here are lower than what is considered a maximum erosion value for agricultural lands being 11.2 t ha^{-1} $year^{-1}$ (FAO, 1988; Schmidt et al., 1982). They are also much lower than what is considered a target erosion rate for rehabilitated mine sites (Welsh et al., 1994; Williams, 2000), and the Australian Queensland Department of Mines and Energy (see Hancock et al., 2019). The values are also similar to what are considered successful geomorphic-based mine restorations in the surroundings. For example, Zapico et al. (2018) measured 4.02 t ha^{-1} $year^{-1}$ at the nearby Machorro mine.

In addition, the above erosion rates, process and location are needed to be placed in context of the site (i.e. the LIFE RIBERMINE restoration). Prior to the geomorphic-based restoration, the reconstructed waste dumps (constructed in 1990) evolved to badlands over the 30 year period to 2020 (see Figures 3 and 15). Martín-Moreno et al. (2018) measured erosion rates of 353 t ha^{-1} $year^{-1}$ on these waste dumps and hillslopes. Post-geomorphic-based restoration (the designs assessed here), SIBERIA predicts only localised gullying. This gullying should not be considered a restoration failure, since the undisturbed surroundings of the mine are subject, naturally, to localized gullying. Indeed, the location of the mine, and surrounding undisturbed catchment (the Peñalen-Merdero watershed) has gullying throughout due to a combination of long and steep hillslopes, highly erodible natural soils and highly erosive precipitation conditions (Martín-Moreno et al., 2018). Therefore, the erosion rates and gullying predicted here, in context of the surrounding nonmined landscape, can be considered low.

6.2 | Geomorphic design and assessment

All landscapes subject to fluvial and diffusive forcing will evolve to form catchments with main drainage lines and hillslopes. The hillslope curves and area-slope relationship of the landscape demonstrate that the design method produces landscapes gemorphically similar to that of natural fluvially evolved catchments. Therefore, constructing a landscape with such geomorphic characteristics places a landscape onto an evolutionary trajectory to which it would eventually evolve to (Guryan et al., 2024; Shobe et al., 2024). In this respect, the GeoFluv method provides a robust design tool for the production of landscapes that have mature fluvial and hillslope geomorphic characteristics.

The landscape was constructed in the year 2020, with monitoring ongoing since then. Initial results demonstrate a good vegetation cover with minimal erosion. The erosion blanket has been effective at

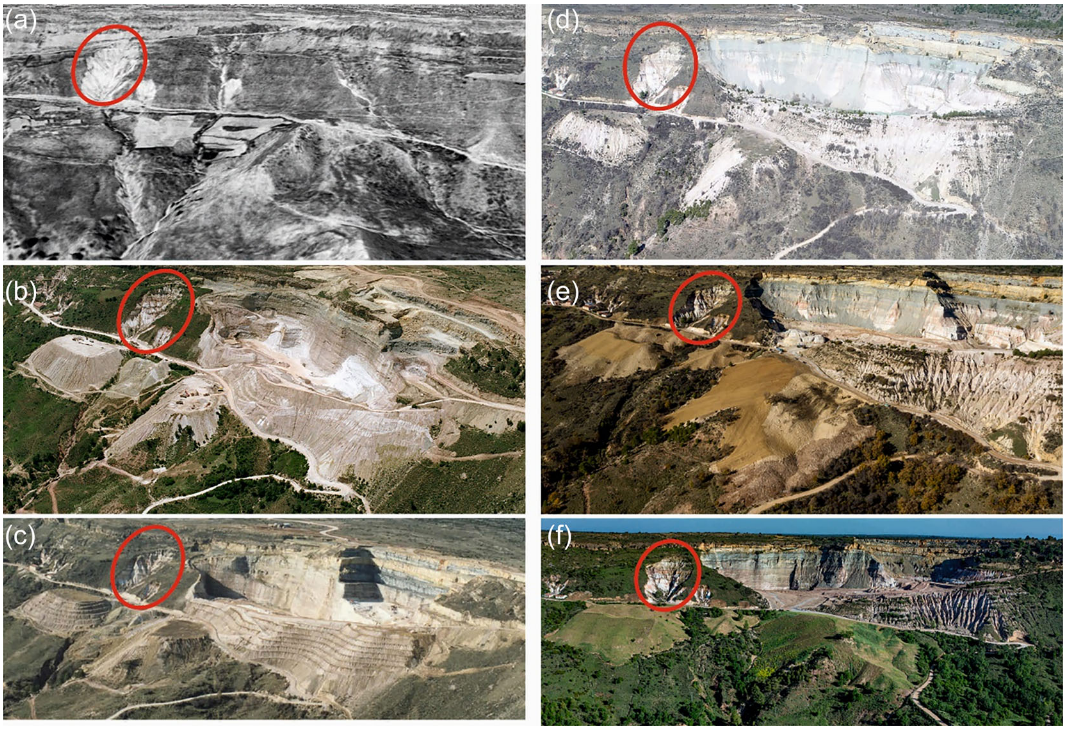


FIGURE 15 Evolution of the Santa Engracia mine, showing stability in the short term after geomorphic-based restoration. (a) Situation in 1956, before the mine (image photorestitued from 1956 IGN a aerial photo Jon Ander Mezo and Ignacio Zapico). (b) Aerial view in 1989, close to mine closure (image by Paisaje Españoles). (c) Aerial view in 1990, after terraced rehabilitation (image by Paisaje Españoles). (d) Aerial view in 2020, showing 30 years of erosion evolution (image by DIEDRO); (e) situation in November 2020, after geomorphic regrading and organic mat installation (image by M.A. Langa); (f) situation in May 2021, after vegetation growing in the first season (restored areas in light green). The site displays a good vegetation cover with minimal erosion. See also Figure 5c. Image by Fotolanga. The red ellipse shows a slope gully for reference. [Color figure can be viewed at wileyonlinelibrary.com]

controlling erosion at least in the short term (see Figures 4c and 15f). Sediment yield monitoring will provide further support.

The authors recognise that the design and assessment method here is not a perfect solution. The design method will always be a compromise and relies on the experience and judgement of the designer based on site constraints and optimising landscape geomorphology. The assessment using a LEM assumes that the model is appropriate and run correctly and that the parameters are appropriate. There is error and compromise in all these steps. Nevertheless, the process provides strong inference as to what can potentially occur and therefore design guidance. A critical final step in this process is monitoring the constructed landform and using the knowledge gained to enhance both the design and landscape assessment process. This methodology presents a new standard for landscape restoration.

It also should be recognised that no site will be completely erosion free. All sites will erode, it is just a question of what is acceptable. The work here demonstrates that gullying is inevitable. However, this gullying is in keeping with the surrounding 'rural' functional landscape. Therefore, any erosion, whether it be sheetwash and or gullying, should be considered in the context of the surrounding landscape. There is also the consideration that it may take several years for any new landscape to evolve initially by rapid erosion to a stable form (Welivitiya & Hancock, 2024). Monitoring provides the means as to what is acceptable and also the landscape trajectory by which decisions can be made to quickly ameliorate any issues.

Monitoring presents an extra cost to this process. In the past, for many projects, the restoration is seen to be completed when the earthworks have been completed with only minimal monitoring and therefore minimal learnings of what has and has not worked. A further point is that records of what work has been done at each site (i.e. underlying materials, topsoil used, ripping and mixing methods, addition of ameliorants, seeding and revegetation) are generally poor or in many cases absent. This provides little guidance as to why sites may be successfully or unsuccessfully reconstructed. In terms of quantifying erosion, the use of LiDAR technology and vegetation mapping allows large areas to be monitored. With high resolution LiDAR and sufficient control points, accurate and reliable erosion monitoring can be undertaken which would demonstrate erosional stability or otherwise. Such a method would demonstrate to the community and regulators the site is on a strong restoration trajectory.

6.3 | Study limitations and future work

The results provided here demonstrate the usefulness of LEMs to assess the strengths and weaknesses of different landscape designs and surface characteristics. However, the parameters employed here are not site specific and have been determined from another nearby site, but with very similar properties. Site specific parameters will provide an enhanced level of confidence. It is planned that site specific parameters will be obtained from detailed surveying of the site using high resolution aerial survey. This will allow refinement of the findings here.

At present, there are no parameters available for the effect of organic mats on erosion reduction. There is also the question of the longevity of the mat and how vegetation establishes and stabilises the surface. The effectiveness and longevity will vary according to site, the materials and climate. The organic mat parameters have been determined from experience of low erodibility systems. There is a need for an understanding of the erosion reduction performance of organic mats and their longevity and the role of climate variability (Cache et al., 2023; Guryan et al., 2024). This will be partially achieved by the proposed site survey.

7 | CONCLUSION

Here, a computer-based LEM has been used to assess reconstructed external waste rock dumps (formerly sidehill type) of a kaolin sand mine in East-Central Spain that has been designed and constructed using geomorphic principles. This is the first time that this assessment method (using a LEM) has been employed in Europe (both for a geomorphic design and for a mine rehabilitation framework) and provides a template for the design and assessment of postmining landscapes.

The results demonstrate that the landscapes are prone to localised gullying. However, erosion is greatly reduced from the abandoned site value of 353 t ha^{-1} year^{-1}. Further, the forecast erosion rates (5.25 and 6.3 t ha^{-1} year^{-1} for EWRD and WWRD respectively) are lower that what is considered a maximum erosion value for agricultural lands and, are similar to erosion rates measured at nearby stable and successful geomorphic-based mine rehabilitation sites (4.02 t ha^{-1} year^{-1}; Zapico et al., 2018). While localised gullying is predicted and likely very similar to the unmined surroundings of the mine, the modelling demonstrates that erosion can be managed by use of an organic mat and vegetation cover. Some gullies may need to be managed by remedial earthworks.

The finding that both erosion processes and rates are similar for both constructed landforms despite differences in maturity (as indicated by hypsometry) suggests that, in this early stage of landscape development, surface properties override landscape properties at this site. Site monitoring and further refinement of parameters employed in the model will enhance the reliability of the predictions here.

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