

Assessing the stability of a geomorphically reconstructed post-mining landscape: a case study of the Santa Engracia mine, Spain

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Abstract

New technology allows for the reconstruction of post-mining landforms using geomorphic design principles. It is important that such designs be evaluated and, if needed, be reshaped so that soil loss is minimised and they geomorphologically and ecologically integrate with the surrounding landscape. One method to assess geomorphic landform designs is to use a computer-based landscape evolution model. Landscape evolution models allow different designs to be input and will highlight where erosion will occur and the type of erosion (i.e. sheetwash, rilling, gully) as well as erosion rate. At the Santa Engracia abandoned mine (East-Central Spain), post-mining landscapes were designed and constructed using geomorphic principles (GeoFluv method and Natural Regrade software). In this design process, the SIBERIA landscape evolution model has been used to assess the erosional behaviour of these landscapes. Results demonstrate that some gully is inevitable. Using suitable topsoil, vegetation and an organic blanket will dramatically reduce erosion, and if vegetation can be established, the modelling demonstrates that the landscapes will have minimal erosion. The erosion forecast is 5.3–15.2 t ha⁻¹ yr⁻¹, an order of magnitude less than the initial erosion rate (~350 t ha⁻¹ yr⁻¹) using conventional (terraced) mine restoration. Further, the erosion rates and localised gully approximate the unmined (natural) Alto Tajo environment. Importantly, with the ability to spatially forecast gully location, erosion reduction measures can be undertaken. Consequently, the method described here provides a robust assessment procedure that can be used at other sites and highlights the potential strengths and weakness of a design process, therefore supporting lower cost with a higher chance of restoration success. The combination of geomorphic landform design and assessment using a landscape evolution at this project presents a new standard for mine rehabilitation in Europe.

Keywords: *geomorphic landform design, geomorphic restoration, GeoFluv, SIBERIA, gully*

1 Introduction

Geomorphic solutions are an area of high interest for post-mining landscapes, as there are many failures (i.e. high erosion rates and low ecological integration with surrounds) of many post-mining landscapes due to poor landscape design and construction. Secondly, hydrological, ecological and visual integration and connectivity with the unmined surrounds are often not — or only partially — considered. A post-mine landscape will be increasingly functional when it is hydrologically integrated with its surrounds.

While the concept of using geomorphic understandings to design a new landscape is not new, the capabilities for designing such complex 3D landforms and drainage networks is non-trivial 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, provides this capability. A second difficulty is the construction of such complex landforms and landscapes, which is now possible with GPS-guidance machine control on large earthmoving 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 (which are not

practical for many sites), numerical soil erosion and landscape evolution models provide a tool for evaluating designs.

There are several numerical models that can be used to assess soil erosion and landscape evolution (Tucker & Hancock 2010; Willgoose 2018). Here, we focus on computer-based landscape evolution models (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; Willgoose 2018). These numerical models employ both fluvial and diffusive erosion processes, together with climate expressed in rainfall amount and intensity. These models are particularly useful for assessing post-mine landscape designs, as they can be input into the LEM and allowed to evolve. Models such as SIBERIA (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).

Here, geomorphically designed landforms are assessed using the SIBERIA LEM at the Santa Engracia mine in East-Central Spain, within the LIFE RIBERMINE project. A range of potential surface treatments are examined. The 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 Methods

2.1 Regional context

The site is located at the edge of the Alto Tajo Natural Park, at the Iberian Mountain Range, East-Central Spain (Figure 1a), within a Natura 2000 network site and a geopark. 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 asl here) 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 1b). 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. Mean annual precipitation is 780 mm and the 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. The spring and fall are usually wet. The rainfall erosive conditions are among the highest in the Iberian Peninsula (see Martín-Moreno et al. 2018).

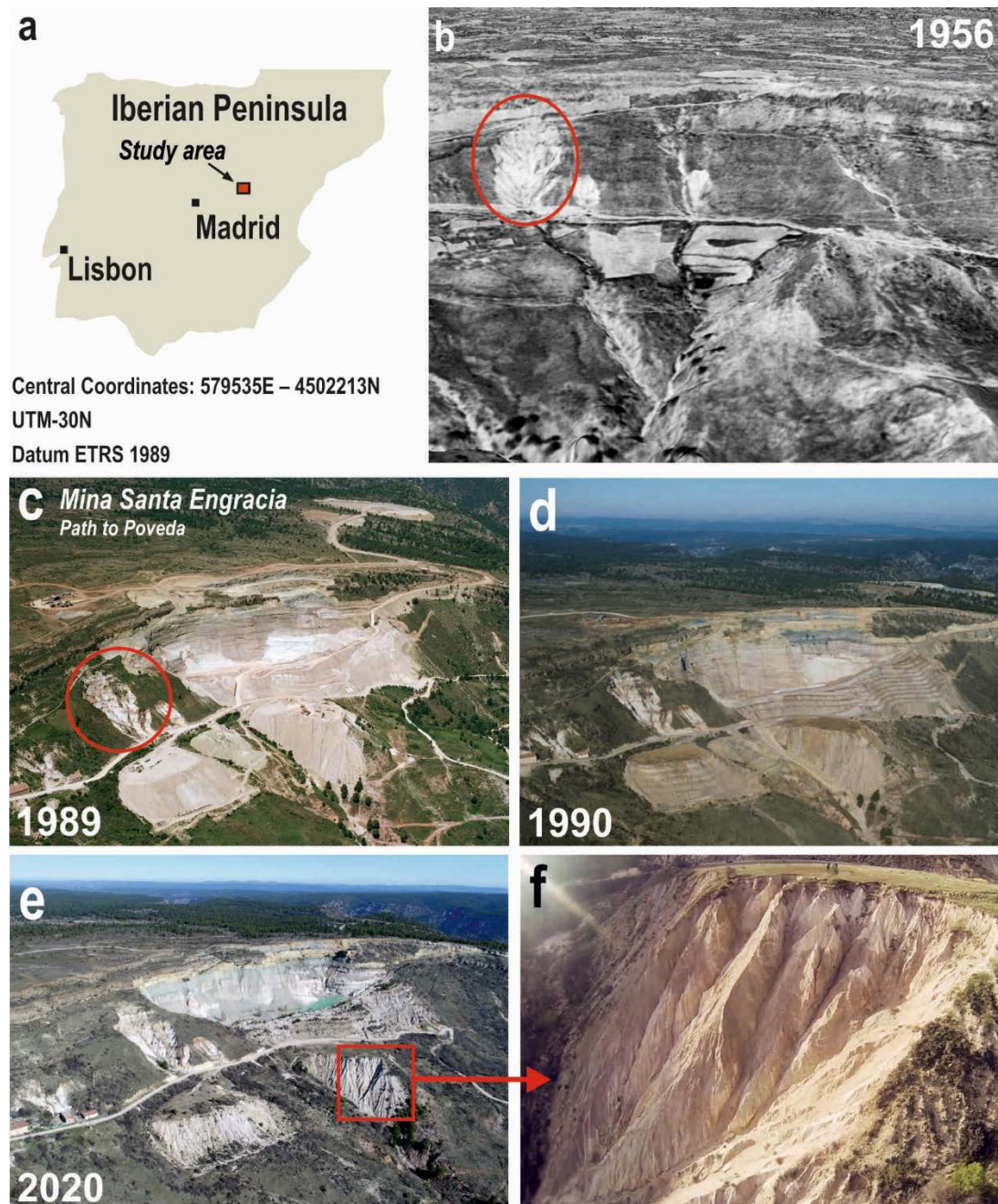


Figure 1 (a) Study area; (b) Reconstructed physiographic setting as for 1956, from aerial photo restitution, of the Santa Engracia Mine, Path to Poveda (image courtesy by JA Mezo Ortiz and I Zapico); (c) Oblique aerial view of 1989 of the Santa Engracia Mine - a sidehill waste dump building process; (d) Site in 1990, restored phase (image by Paisaje Españoles); (e) Site in 2020, showing 30 years of erosion evolution (image by DIEDRO); (f) Detail of the severe (30-m high) gullying-badland erosion occurred after restoration, from 1990 to 2020, at the external east waste rock dump (image by DGDRONE).

2.2 The LIFE RIBERMINE project

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 focuses on abandoned kaolin mines of Peñalén (Guadalajara province).

The pre-restoration scenario evolved from a conventional (terraced) restoration (Figure 1d) to a heavily gullied hillslope (badland), with an erosion rate of $353 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Martín-Moreno et al. 2018) (see Figure 1d, f, g). The sediment yield from these highly eroded waste dumps is hydrologically connected with the Tajo River within the Natural Park, resulting in extremely poor water quality and considered the most significant environmental problem of the Alto Tajo Natural Park. Therefore, the goal of LIFE RIBERMINE project was to remove the source of sediment entering the Tajo fluvial ecosystems by ecological, geomorphic-based restoration of the Santa Engracia mine. In comparison, erosion rates for the Alto Tajo natural environment are low, with Zapico et al. (2018) reporting rates of approximately $4 \text{ t ha}^{-1} \text{ yr}^{-1}$.

2.3 Geomorphic landscape design and construction

For the design of the rehabilitated landforms on unconsolidated waste dumps at the Santa Engracia mine, the GeoFluv method, through the Natural Regrade software, was used (Figure 2). A description of the method is provided elsewhere (Bugosh & Epp 2019; Martín Duque et al. 2020, 2021; Zapico et al. 2018). The application of this method to a scenario with high steep gradients (both for the waste dumps and the natural hillslopes on which they are located), led to the development of a new geomorphic landform restoration model for sidehill waste rock dumps (for such WRD typology, see Orman et al. 2011). This consists of transforming a typical platform-outslope topographic model (Figure 2a) into a series of sub-catchments, which blend geomorphically with the surrounding undisturbed terrain (Figure 2b and c). The method requires 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 moving earth downhill, connecting the sub-ridges and swales with those of the natural slope. Between the bottom of the valley and the scalloped hillslope, a small divide provides a transition between the two landforms (see Figure 2c). In short, the initial linear platform and outslope with benches are reconstructed to a surface that consists of a series of catchments with natural hillslope curvature and a constructed drainage line. An overall view of the pre-construction and post-construction landscape constructed in 2020 is displayed in Figure 3.

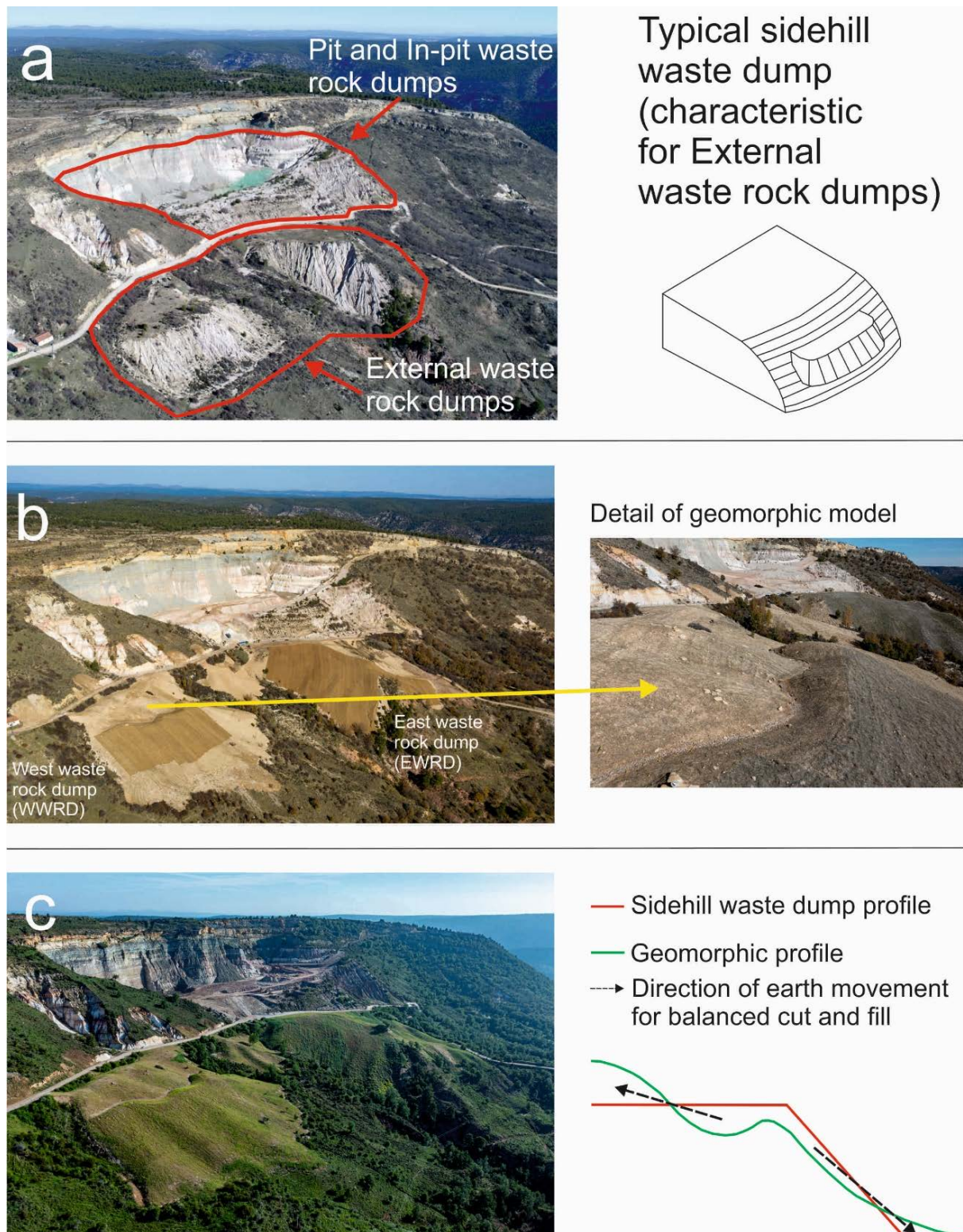
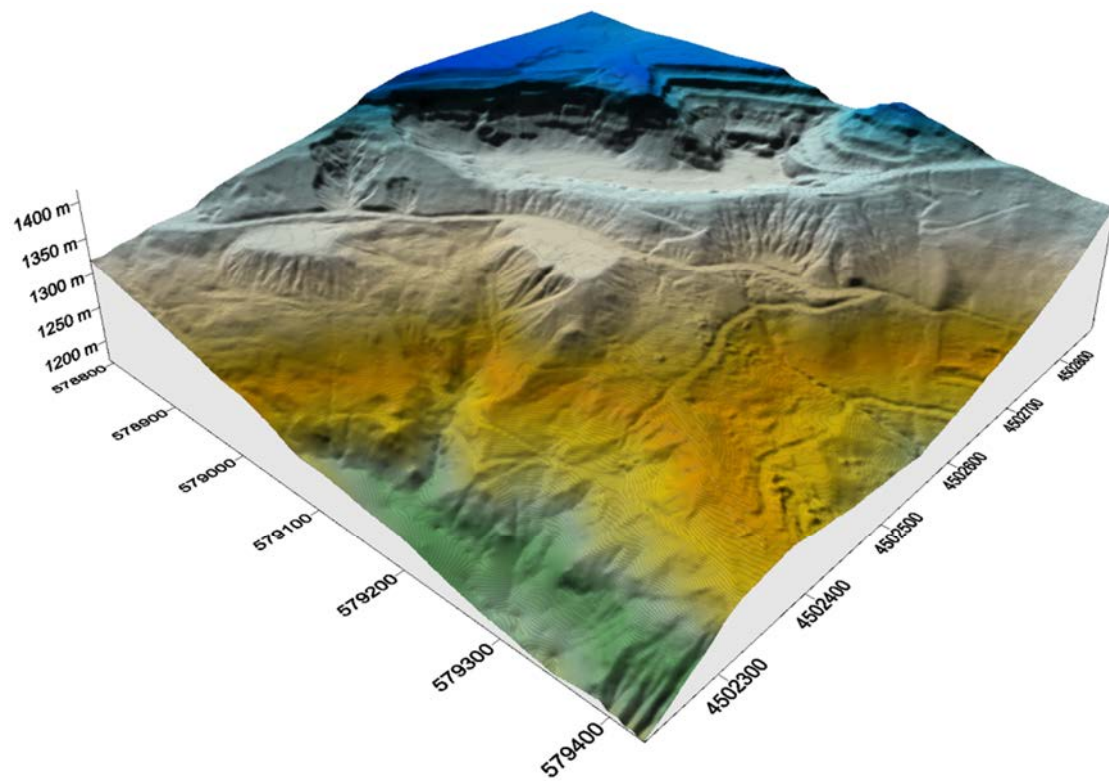
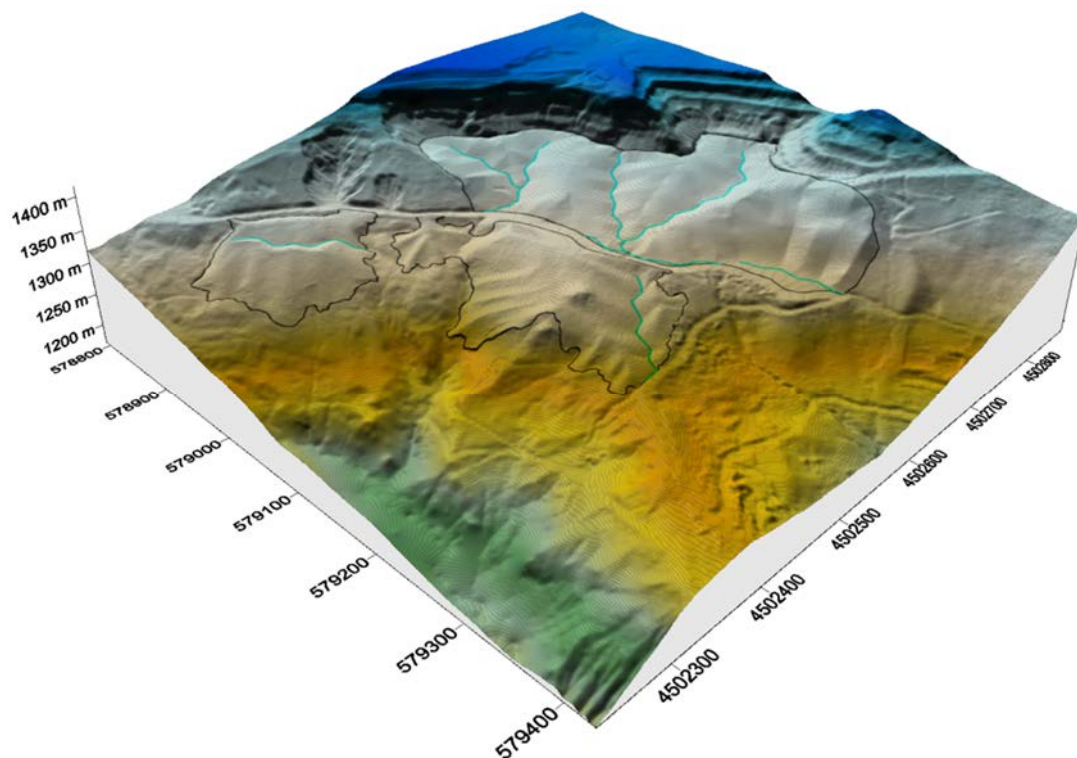


Figure 2 Santa Engracia mine, Path to Poveda site. (a) Pre-restoration scenario (March 2020, image by DIEDRO) - notice the generalised gully-badland topography, indicator of severe erosion, and the typical sidehill morphology at the External waste rock dumps (scheme redrawn from Orman et al. 2011); (b) Post-geomorphic 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



(a)



(b)

Figure 3 (a) Pre-restoration topography of the Santa Engracia mine; (b) Geomorphic landform restoration design, through GeoFluv-Natural Regrade, showing: the limits of the designs (black line) and the main designed fluvial channels (blue lines). The landforms downslope of the road in the centre of the image (External waste dumps) are the focus of this paper

2.4 Landform assessment method

The geomorphically designed landforms were assessed using the SIBERIA landscape evolution model. The outcomes will allow (a) undertaking soil erosion control, if needed, at the forecasted gully location; (b) evaluating with ground truthing the fit between the erosion occurrence and the modelled gully.

The two waste dumps restored in 2020 are termed East Waste Rock Dump (EWRD) and West Waste Rock Dump (WWRD) (Figure 4). The EWRD and WWRD have areas of 3.25 ha and 1.82 ha, respectively (Table 1). Both sites had steep average slopes.

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. This material was obtained from both former surficial deposits and soils (removed by the mining activity, mixed with the wastes) and from the surrounding landscape.

Due to the steepness and high erodibility of the site, an organic mat (erosion control blanket) was placed over high slope areas of the surface of the External waste dumps. This erosion control blanket (Fijavert HC350; <https://www.projar.es/>) was a mat that 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.

Table 1 Site characteristics for the geomorphically constructed landscapes at the External waste rock dumps

	West waste rock dump (WWRD)	East waste rock dump (EWRD)
Area	1.82 ha	3.25 ha
Elevation range	48 m	47 m
Average slope	37%	36%

2.5 Landscape evolution model

SIBERIA is a LEM that has been used extensively for erosion on post-mining landscapes by the mining industry and was first used in the 1990s (Hancock & Willgoose 2018).

SIBERIA provides (a) visualisation of erosion and where it occurs (i.e. gullies, rills) and (b) an erosion rate, both in $\text{t ha}^{-1} \text{yr}^{-1}$ and denudation (mm yr^{-1}) (i.e. landscape lowering).

2.5.1 Model parameters

Calibration at this site has been based on similar materials at the 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 control the form of erosion. The values of m_1 and n_1 vary widely, but for most landscapes, they both range between 1 and 3 (Kirkby 1971).

Table 2 Parameters employed for the SIBERIA modelling for the Santa Engracia mine

Parameter	High erosion	Organic mat	Post-organic mat
β_1 (erodibility)	0.02	0.001	0.002
m_1 (exponent on discharge)	2.0	1.2	2.0
n_1 (exponent on slope)	2.1	2.1	2.1
β_3 (rate constant on area)	1	1	1
m_3 (exponent on area)	1	1	1

2.5.2 Landscape and digital elevation model data

Topography of the constructed landform was obtained by structure from motion photogrammetry combined with an unmanned aerial vehicle (SfM-UAV) technique (Figures 3 and 4). This data was then gridded using Kriging to a regular grid spacing of 0.5 m, with the EWRD and WWRD extracted from this data. 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.

3 Model setup

The landforms were designed using a geomorphic approach (GeoFluv-Natural Regrade) that 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 3 and 4). Such landforms have a series of sub-catchments 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 3). The EWRD consisted of a longitudinal catchment to the east and a main scalloped hillslope to the west.

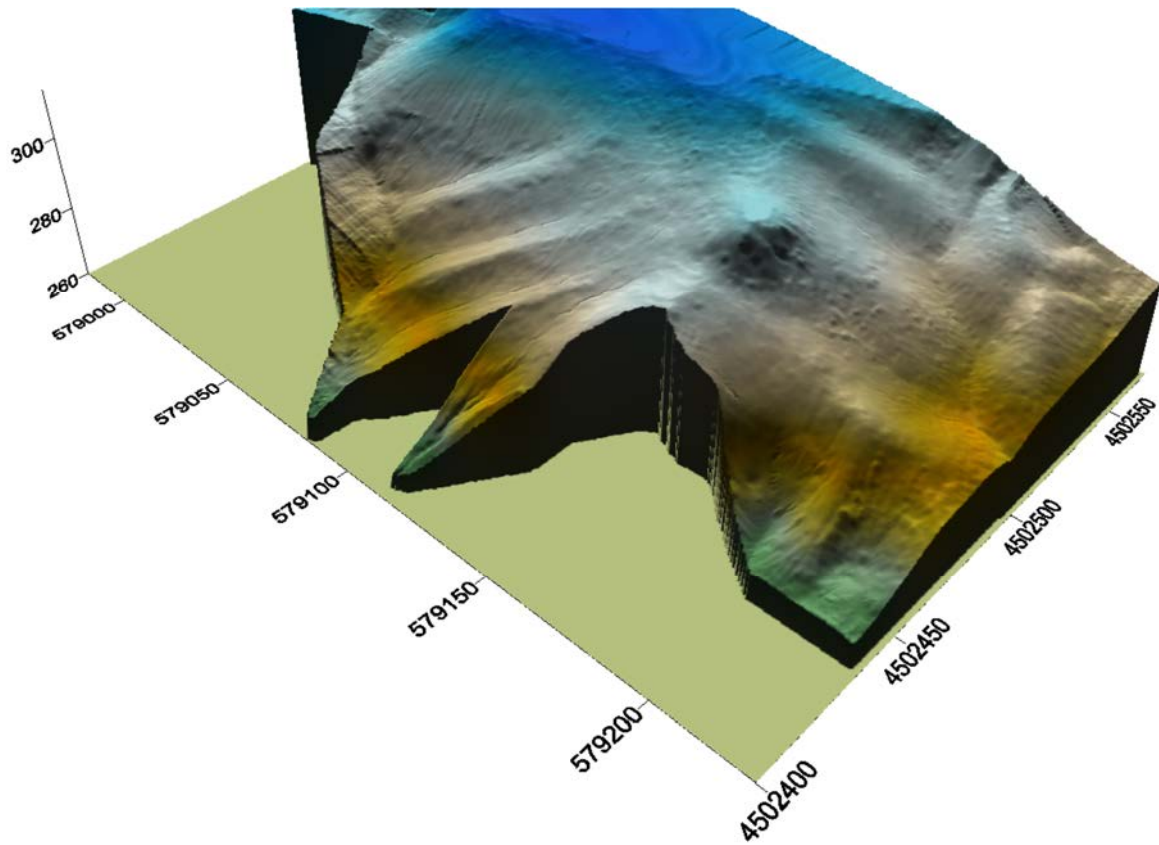
The SIBERIA model was run using the parameters described above (Table 2). The model was run for the entire landscapes, with sediment free to leave from the DEM boundaries (Figure 4).

The simulations performed here were:

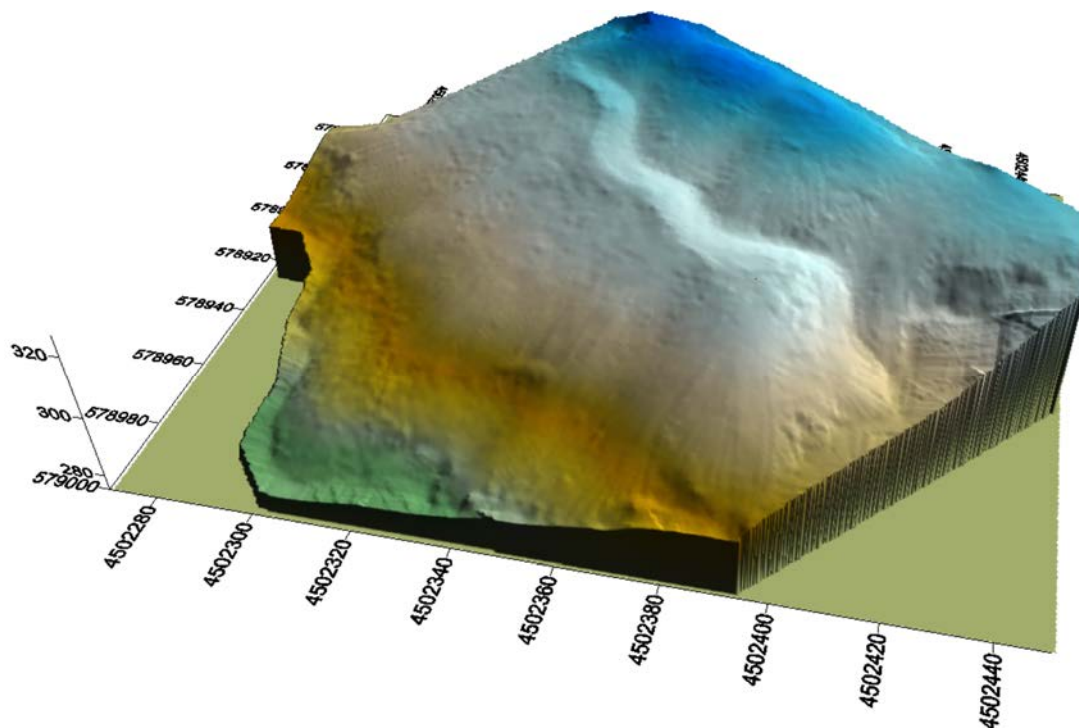
1. High erosion and organic mat simulations for 100 years. High erosion is a worst-case scenario, and the use of the organic mat represents an ideal theoretical situation with minimum potential erosion.
2. The organic mat parameters were run for three years, then restarted at year 4 with post-organic mat parameters. A three-year period represents an initial low erosion rate and allows drainage lines to form. The model run was then continued for 100 years with post-organic mat parameters. This is the most realistic situation field situation.

All modelling was continued for a length of 100 years, as it is considered to be within a human management time frame. 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.



(a)



(b)

Figure 4 (a) External east waste rock dump; (b) External west waste rock dump. All dimensions are metres. Z values are "above 1,000 m asl"

4 Results

4.1 High erosion

This 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 5 and 6).

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 with maximum depths of 2.8 and 3.4 m for the EWRD and WWRD.

Of note here is that both the hillslopes and channels are prone to gullying. The erosion rates are similar for both landscapes ($\sim 14 \text{ t ha}^{-1} \text{ yr}^{-1}$) (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.

4.2 Organic mat

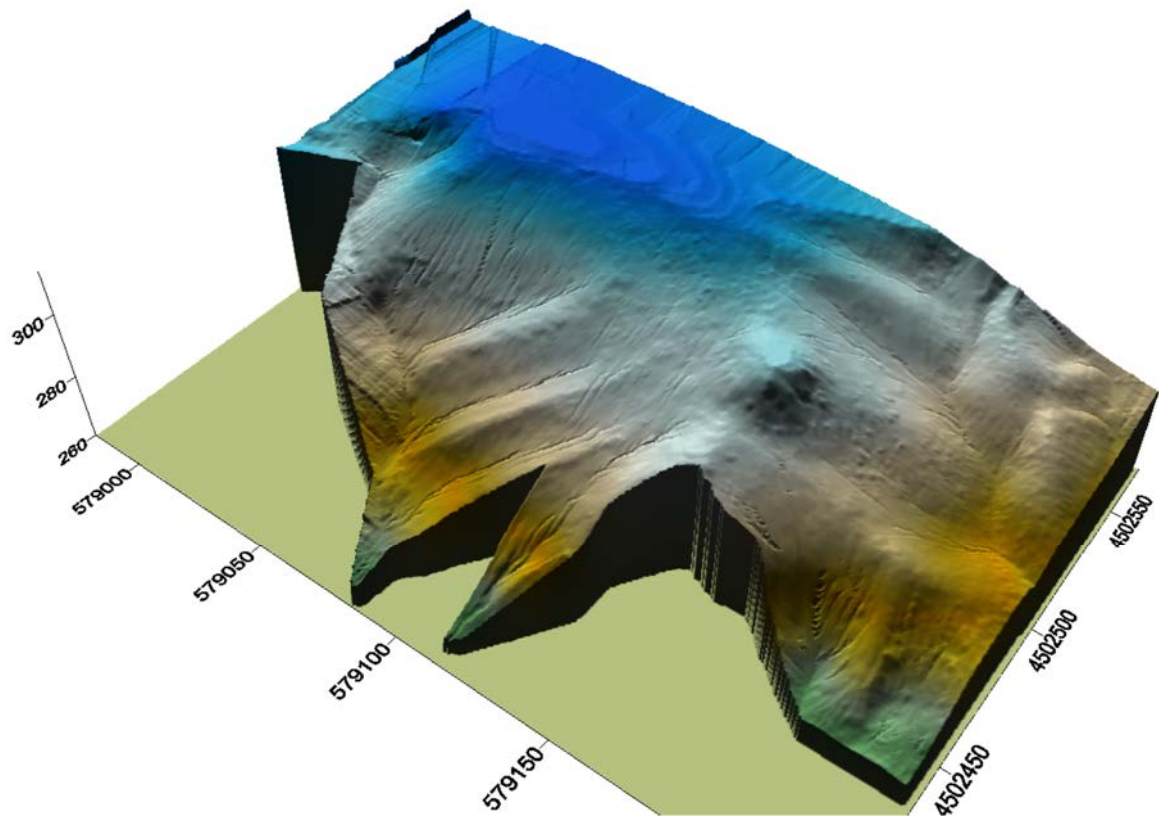
This modelled scenario assumes a constant and stable organic mat cover for the 100-year period. Using organic mat parameters, there is little erosion (not shown for brevity). It is hard to discern any visible rilling or gullying. Erosion occurs by sheetwash.

For the EWRD, maximum depth of erosion at 100 years is 0.36 m, with an average erosion rate of $1.3 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Table 3). Maximum erosion depth for the WWRD is 0.82 m at 100 years, with an erosion rate of $1.2 \text{ t ha}^{-1} \text{ yr}^{-1}$.

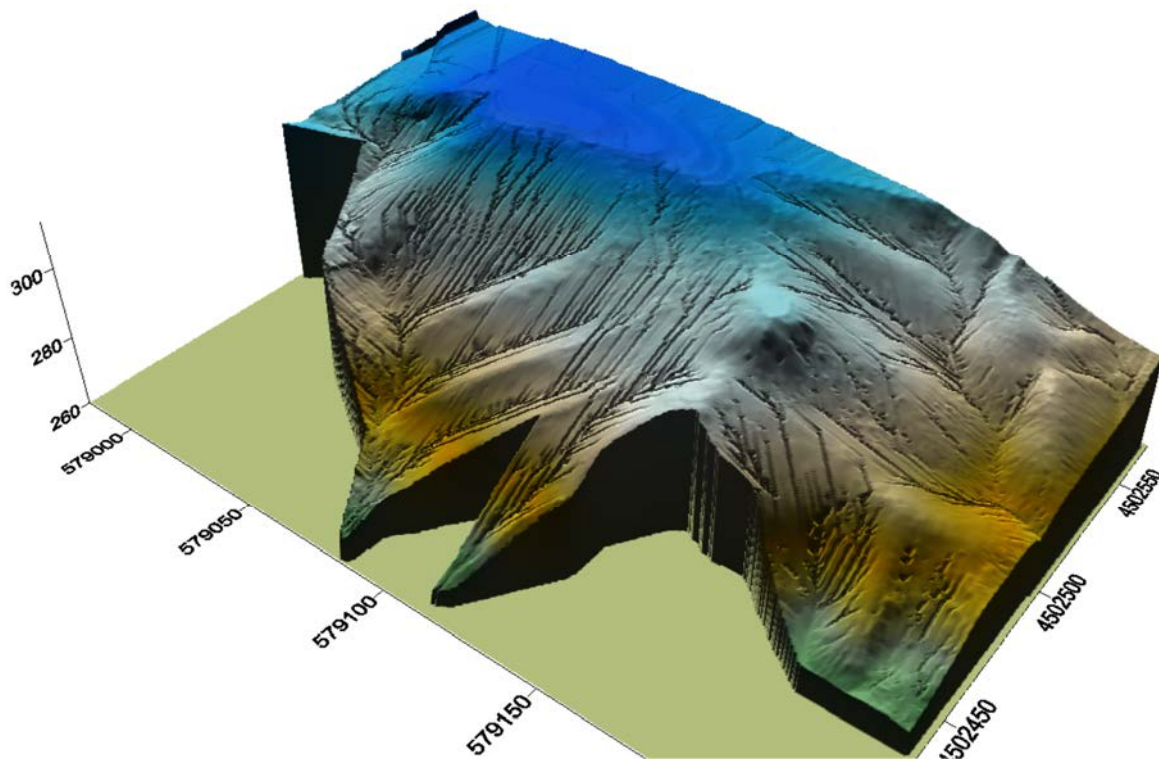
4.3 Post-organic mat

This assessment used organic mat parameters for three years, then used the high erodibility parameters for the following 100 years (Figure 7). The results demonstrate that at 10 years there is minor gullying for both the EWRD and WWRD (Table 3). After 10 years, gullies begin to form and are quite visible at 50 years, with both hillslope and channel having gullies present. The gullies continue to grow with time.

The erosion rate is relatively low ($5\text{--}6 \text{ t ha}^{-1} \text{ yr}^{-1}$); however, at 100 years, the gullies are over 2 m deep for both landscapes.

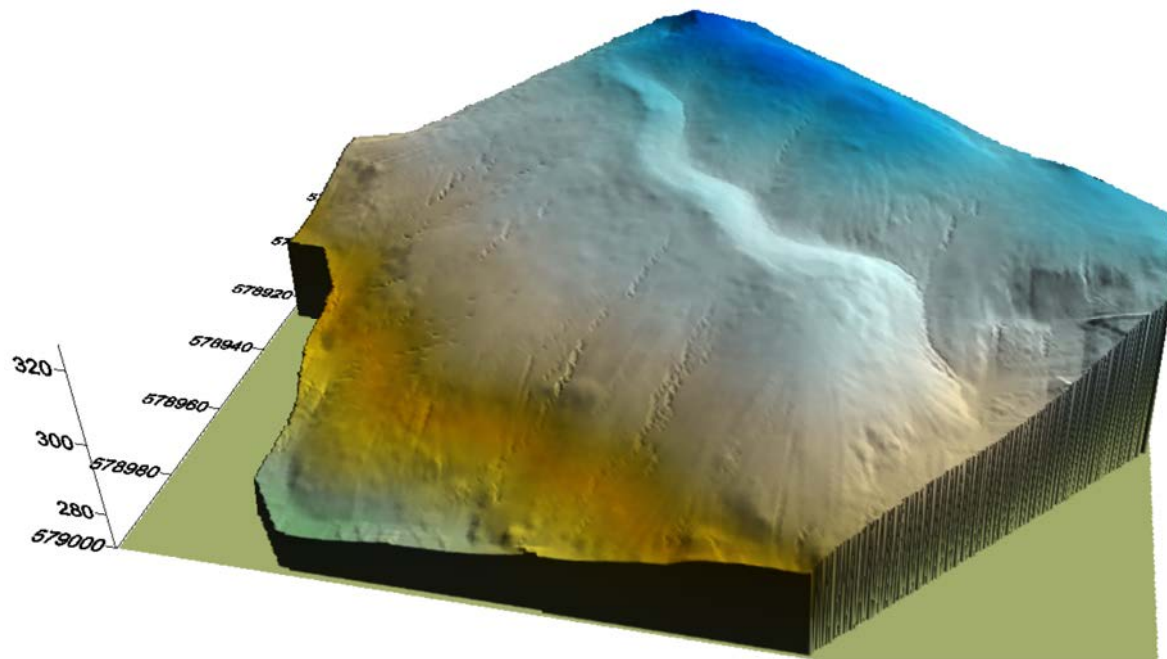


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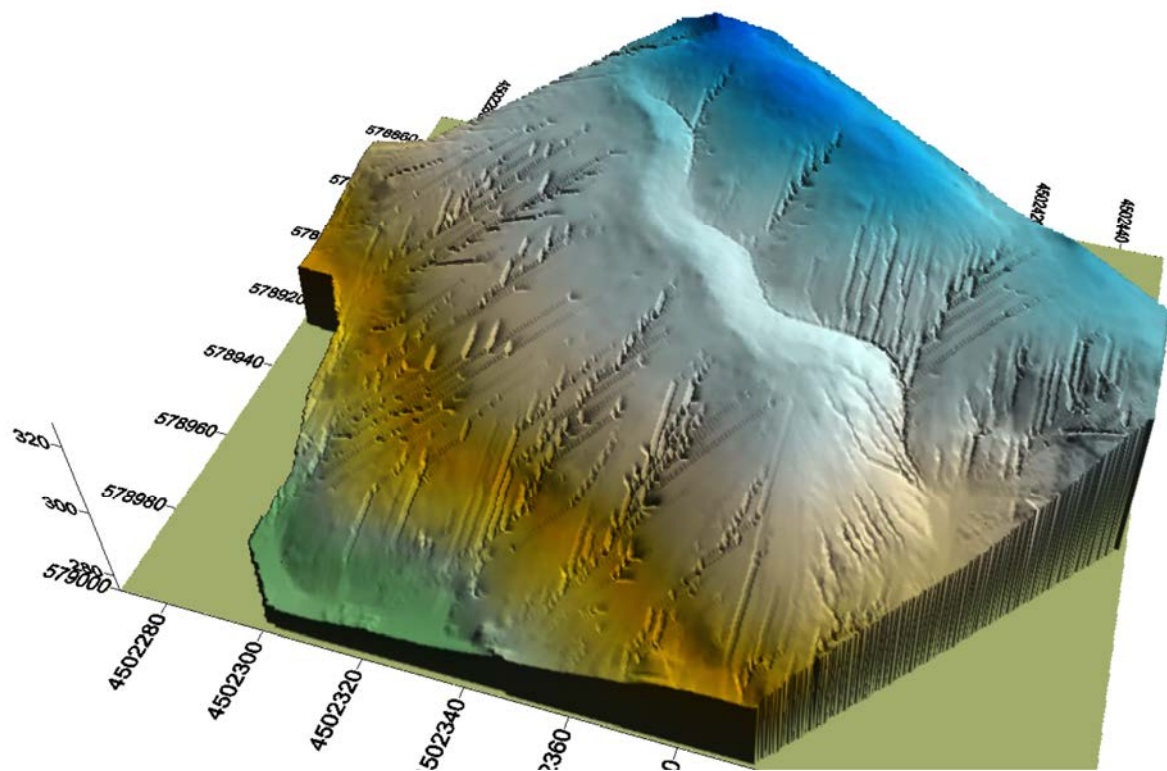


(b)

Figure 5 East waste rock dump initial landscape initial surface at (a) 10 years and (b) 100 years using high erosion parameters. All dimensions are metres

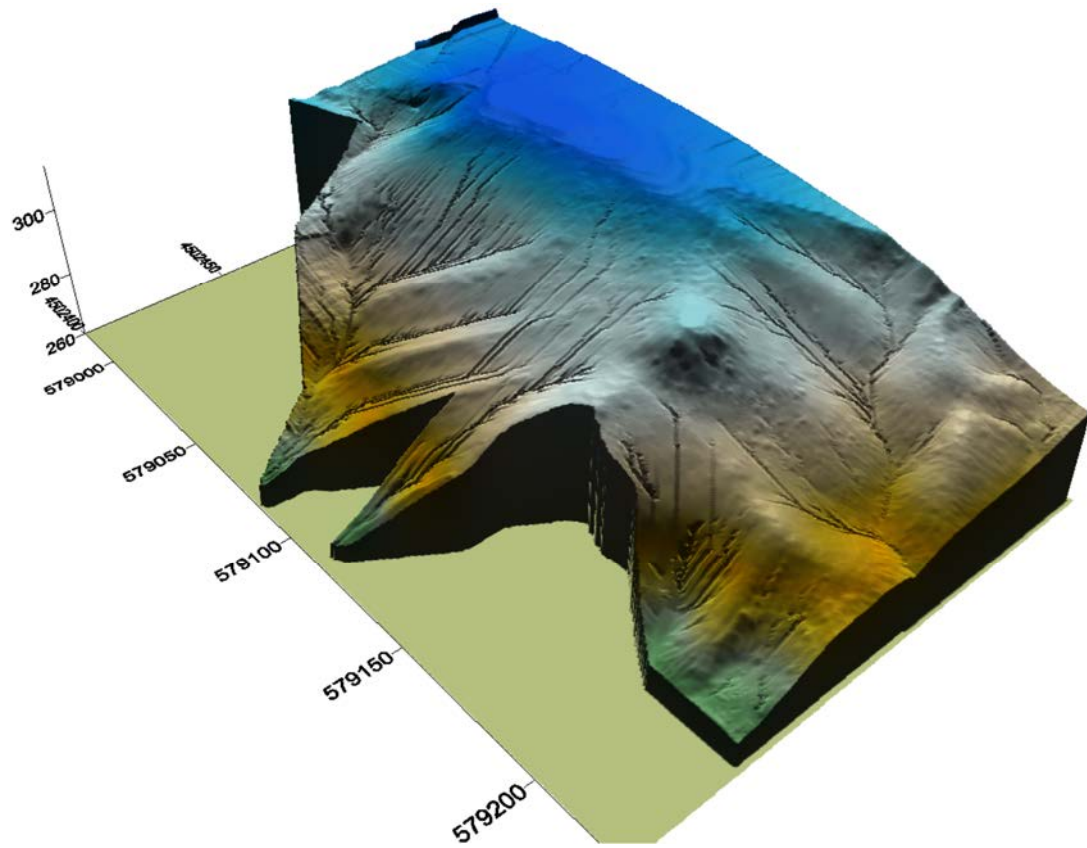


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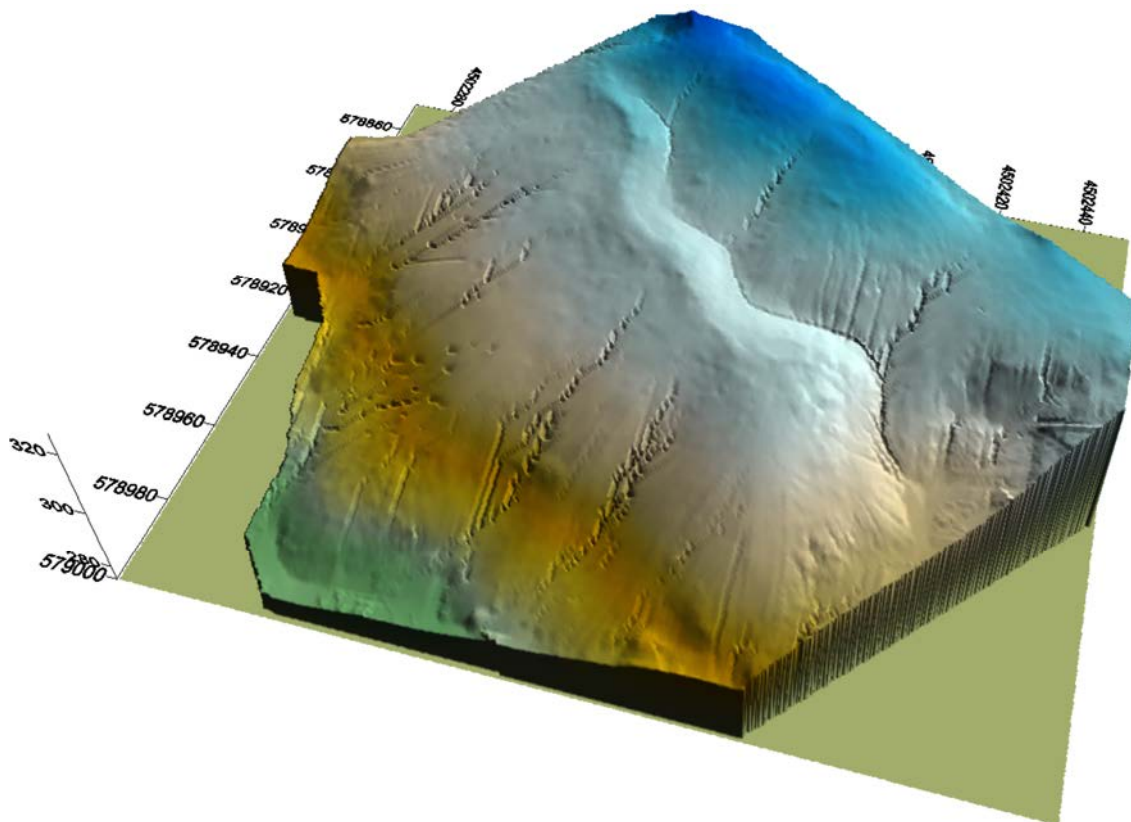


(b)

Figure 6 West waste rock dump initial landscape at (a) 10 years and (b) 100 years using high erosion parameters. All dimensions are metres



(a)



(b)

Figure 7 (a) East waste rock dump and (b) West waste rock dump at 100 years using post-organic mat parameters (Scenario 3)

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 yr⁻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 yr⁻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
Post-organic mat				Post-organic mat		
Erosion rate (t ha⁻¹ yr⁻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

5 Discussion

The design approach described here aims to emulate geomorphic landforms based on an understanding of the surrounding landscape, the surface materials and climate. Any landscape design should be evaluated for its erosional stability. LEMs provide a framework for landscape assessment and will highlight strengths and weaknesses. 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 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.

5.1 Erosion characteristics

Both WWRD and EWRD 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 the 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.

Employing post-organic mat parameters demonstrates that the landscapes are largely stable, with erosion low rates comparable to the Alto Tajo natural environment (Zapico et al. 2018; 2020 report rates of approximately 4 t ha⁻¹ yr⁻¹). The maximum rates for 100 years (see Table 3) are 5.25 and 6.3 t ha⁻¹ yr⁻¹ for the EWRD and WWRD, respectively. Given that the erosion rate for this landscape, before restoration, was 353 t ha⁻¹ yr⁻¹, this is a very positive outcome. Post 10 years, gullies are predicted to form both on 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 $11.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ (FAO 1988; Schmidt et al. 1982). The values are also similar to what are considered successful geomorphic-based mine restorations in the surroundings. For example, Zapico et al. (2018) measured $4.02 \text{ t ha}^{-1} \text{ yr}^{-1}$ at the nearby Machorro mine.

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. Martin-Moreno et al. (2018) measured erosion rates of $353 \text{ t ha}^{-1} \text{ yr}^{-1}$ on these waste dumps. 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 gullying. Therefore, the erosion rates and gullying predicted here, in the context of the surrounding non-mined landscape, can be considered low.

5.2 Further considerations

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 have 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 (such as this site). This provides little guidance as to why sites may be successfully or unsuccessfully reconstructed. Improved record keeping and monitoring would demonstrate to the community and regulators that the site is on a strong restoration trajectory.

6 Conclusion

All landscapes subject to fluvial and diffusive forcing will evolve to form catchments with main drainage lines and hillslopes. The hillslope curvature of the landscape demonstrates that the design method produces landscapes geomorphically 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. In this respect, the GeoFluv method provides a design tool for the production of landscapes that have mature fluvial and hillslope geomorphic characteristics.

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. There may be other solutions available. The assessment using an LEM assumes that the model is appropriate and runs 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.

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 in this environment 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. Monitoring provides the means to assess what is acceptable and also the landscape trajectory by which decisions can be made to quickly ameliorate any issues.

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