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Geomorphic rehabilitation, landscape evolution and hydraulic modelling for the closure of Cerrejón mine, Colombia

José Francisco Martín Duque [a,*], Gregory Raymond Hancock [b], María Tejedor [a], Ernest Bladé [c], Ramón Sánchez [a,d], Álvaro Gómez [e], Carlos Alberto Fuentes [e], Luis Fernando Madriñan [e], Juan Pablo Lozano [e], Eduardo Castro [e]

[a] *Complutense University of Madrid, Spain*

[b] *The University of Newcastle, Australia*

[c] *Polytechnic University of Catalonia, Spain*

[d] *Vast-la, Sweden*

[e] *Department of Environmental Management, Carbones del Cerrejón Limited, Colombia*

Abstract

This paper describes the first use of geomorphic landform design (GLD) and landscape evolution modelling (LEM) for mine rehabilitation and closure in a South American context. These methods are being applied at the largest open pit mine on this continent and one of the largest worldwide: Cerrejón (Colombia). GLD (using GeoFluv-Natural Regrade software) is being introduced here at several large waste rock dumps (WRD) without jeopardising volume storage or footprint requirements, with clear advantages in terms of predicted water erosion stability – aiming to avoid 'spillage' erosion processes from platforms and berms – and ecological, hydrological and visual integration with the surroundings. However, some challenges are yet to be solved, such as minimising earth movements for the reshaping of existing WRD and a fluent integration between geomorphic designs and mine planning. The SIBERIA modelling always forecasts less erosion rates for the geomorphic alternatives than for the conventional topographies, with very significant differences at one site (La Estrella WRD) and with one order of magnitude of difference: 66.1 t ha^{-1} yr^{-1} predicted for conventional topography and 6.9 t ha^{-1} yr^{-1} for geomorphic, for year 300. The geomorphic designs are prone to some localised gullying in the main drainage lines, but this maximum erosion (gully) depth is around one third less than for the conventional alternative. This modelling is preliminary and provisional until proper calibration for the site will be available. However, with the same parameters for both modelling sets, the tendencies are clearly in favour of the geomorphic alternative. In order to better understand this gullying process at the drainage lines, and to avoid it, the GLD for the Cerrejón mine is being subjected to hydrologic and hydraulic modelling with Iber, a 2D hydraulic model for the simulation of free surface flow in rivers. This allowed us to obtain water depths and velocities, bed shear stresses and critical diameters for each drainage line of the GLD. With this information, armouring or hydraulic works are being designed.

Keywords: *mine rehabilitation, mine closure, geomorphic landform design, landscape evolution models, GeoFluv, SIBERIA, Iber, Cerrejón*

1 Introduction

The most common landform design for mine rehabilitation and closure worldwide is to construct linear and benched (terraced) landforms in combination with contour drains, downdrains and/or contour banks, positioned at regular intervals. There are technical, economic and traditional reasons for such global practice, such as increasing volume storage in a minimal footprint, geotechnical stability, ease of construction and continuation of the practices that have been taught and learnt for decades. Depending on the specific

* Corresponding author.

topographic characteristics, material properties, soil, vegetation and climate, these landforms can be metastable or highly unstable regarding water erosion. In addition, the combination of inclined planes (outslopes) and benches seldom blend with the surrounding landscapes.

Since the 1990s, a different tactic has been progressing to design mine landforms for rehabilitation and closure. This alternative involves a paradigm shift. It uses a fluvial geomorphology to organise the post-mining landscapes into catchments with drainage networks and 3D convex-concave hillslopes which replicate natural systems. The aim is not to replicate the pre-mine topography, since the characteristics of such terrain are always very different than those of wastes or tailings. Instead, the catchment approach seeks to increase terrain stability against water erosion from the short to long term and maximise the inherent visual, hydrologic and ecologic integration with the environment. These procedures have received different names, such as 'geomorphic' followed by 'approach', 'reclamation', 'rehabilitation', 'restoration' or 'landform design'.

Geomorphic landform design (GLD) consists of changing the conventional terraced landforms and related drains into a 'drainage basin' with catchments designed and built to stand as closure and rehabilitation final landscapes. The new methodology surfaced after the *Surface Mining Control and Reclamation Act 1977* (Office of Surface Mining Reclamation [OSMR] 1977) requested that mine rehabilitation landscapes '…blend into and complement the drainage pattern of the surrounding terrain'. This simple sentence introduced and proposed the drainage basin as the basic unit for mine rehabilitation. Conceptually the approach meant a radical change, driven by scientific and technological innovations, to the existing 'business as usual' waste rock dump (WRD) (or tailing storage facilities, TSF) design and construction. This change is occurring globally and steadily, but it is spreading slowly.

The geomorphic approach was first introduced at disturbed minelands in Canada in the early 1990s. Liability issues were key because oil sand mining companies in Northern Alberta were reticent to incur long-term responsibility following mine closure, with a regulatory request for closure systems designs to prevent future environmental catastrophes by construction failures and natural hazards. One option was to use the conventional risk-based approach based on specific failure events with recurrence intervals beyond a 2000 base year. But this option would be very costly and would result in closure drainage solutions that did not resemble natural ecosystems. The geomorphic approach was then introduced so the constructed systems would perform similarly to the natural ones, with comparable erosion rates. The resulting closure drainage systems would avoid the unsightly appearance of concrete downdrains while providing natural-like landforms and ecosystems at significantly lower costs. Natural drainage systems which evolved in response to natural events were then far more robust than conventional structurally engineered interventions. This geomorphic approach requires a sound understanding of natural systems so the analogues of nearby untouched environments can be accurately replicated. Adaptation of the geomorphic approach has continued for more than 30 years in this region of Canada. It is notable that in Canada the mining companies lead the promotion and support of the geomorphic approach as a more efficient, cost-effective and ecologic solution (Sawatsky & Beckstead 1996; Sawatsky, pers. comm.).

In parallel, in the US, the benefits of having a comprehensive fluvial geomorphic approach to integrate 'natural' stream drainage systems and upland landforms, as SMCRA had envisioned, were recognised but not yet successfully implemented. In 1997, 20 years after the passage of SMCRA, mine operators and regulatory authorities in the US were finding that disturbed land reclamation works were not meeting all criteria for complete bond releases. Two years later, in 1999, operators were only meeting 66% of OSMR's bond release target acreage (Bugosh & Eckels 2023).

Also in 1999, a BHP mine operation in the highly erosive New Mexico environment, recognising the problems accompanying conventional reclamation practices, began applying geomorphic reclamation. It combined the upland and stream channel elements into a stable landform. The uplands included 3D scalloped convex-to-concave hillslopes that broke long slopes into smaller ridges and swales (depressions). The designed landscape was dissected by stream channels aimed at transporting the flow from the valley walls. The swales on the valley's slopes conveyed the water to the channels in a non-erosive way. The hydrologically-balanced channels transferred the run-off and sediment to the local base level, just as in a mature, stable, steady-state landform.

This is how Nicholas Bugosh invented the GeoFluv method. Its benefits include improved stability against erosion and the ability to conserve water in a semi-arid environment for lower costs, and results in greater diversity in vegetation and wildlife habitats plus reduced maintenance requirements, all of which promoted successful bond releases. These advantages were presented at an Alternatives to Gradient Terraces Workshop (Bugosh 2000). This method was used at a sister mine in 2002 and that project was recognised by OSM as the 'Best of the Best' US mine reclamation in 2004 (Bugosh & Eckels 2023). GeoFluv was implemented in a specific software in 2005 (Carslon Natural Regrade). From the US and Canada, geomorphic rehabilitation of mined sites spread to Australia (Waygood et al. 2014) and Europe (Zapico et al. 2018; Martín Duque et al. 2021a, 2021b). In Australia, after preliminary use of GeoFluv-Natural Regrade, C. Waygood and S. Dressler from WSP are now successfully leading a broad application of geomorphic rehabilitation, mostly in the Hunter Valley of New South Wales, but also in other states (Dressler & Waygood 2022).

In parallel to the development of GLD, experts on erosion at mined sites were realising that the conventional use of erosion plots and related models, such as universal soil loss equation (USLE), were not quite suitable to study erosion at mined sites. The rationale behind this statement is erosion plots and associated USLE models only forecast sheet erosion or rilling. At a landscape (or watershed) scale, however, as is typically the case with mining sites, what mostly occurs is gully erosion that is often not directly related to rainfall impact on the soil but by concentration and overflow of surface water from platforms and benches. In this regard, the use of landscape evolution modelling (LEM) such as SIBERIA or CAESAR is widely used in predicting erosion in minescapes. In Australia, SIBERIA has been used for more than 30 years (Hancock et al. 2017; Hancock and Willgoose 2018). The use of CAESAR is quickly increasing as well, coupled with geomorphic design (Slingerland et al. 2022).

In summary, GLD and LEM are relatively well-known and applied, separately or jointly, in mine rehabilitation and closure in the US, Canada, Australia and some European countries (such as Spain and Sweden). However, they are not yet well developed in the rest of the world. This paper describes the joint use of GLD and LEM at the largest open pit mine in South America, Cerrejón (Colombia); being the first mine in the South and Central American region to adopt such mine rehabilitation and closure solutions. Cerrejón is embracing these innovative methods, searching for more efficient, resilient and ecologically beneficial results. Thus this company is self-imposing higher standards of rehabilitation and closure than those requested by the Colombian mining authorities. The shift towards a geomorphic approach seeks, primarily, to avoid gullying of the terraced rehabilitated landforms; a process that has been reported elsewhere (Martín-Moreno et al. 2018). This process occurs here also as characteristic 'spillage erosion', once the water accumulated at the flat top areas and benches of the WRD overflows the bunds built to avoid run-off. Similarly to the shift that Canadian oil sand companies made, Cerrejón seeks to design and build more cost-effective closure landscapes to perform like the natural drainage of the surroundings, be more resilient in response to extreme natural events, and blend ecologically and visually with the surroundings.

2 Physical environment

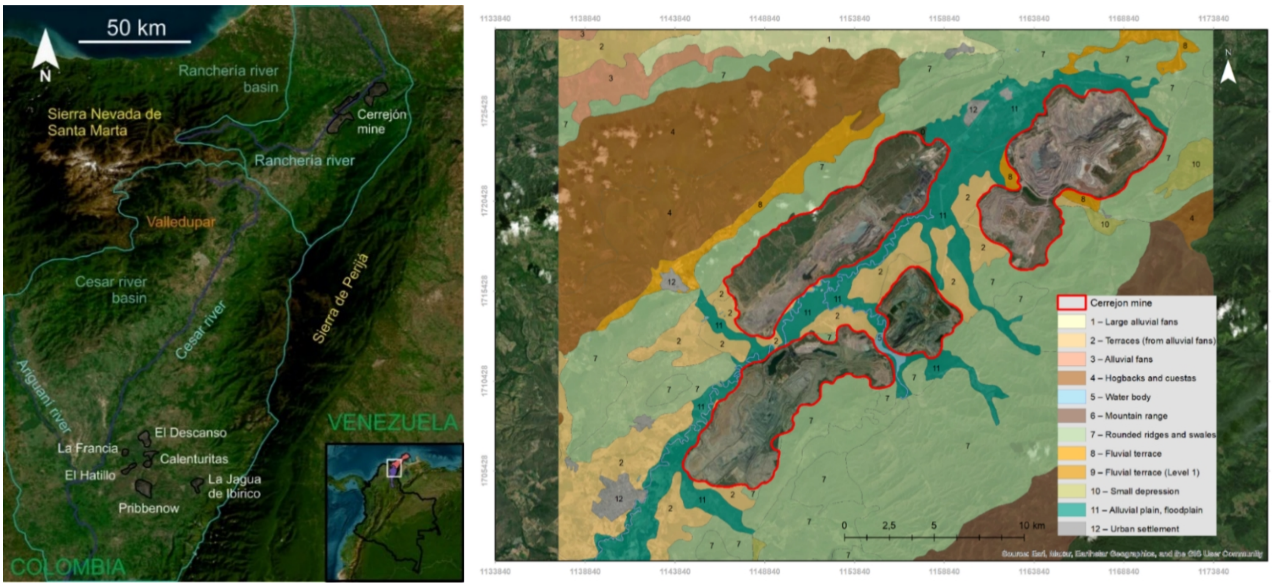
The Cerrejón coal mine lays within the Cesar-Ranchería Basin, which creates a well-defined geographical unit, the Cesar-Rancheria Valley, in northeast Colombia. This is a sedimentary basin formed by a tectonically subsided block that is rich in coal deposits of the Paleocene Cerrejón Formation. The basin covers the southern part of La Guajira and the northern portion of the Cesar Colombian Departments. Two mountain ranges enclose a narrow triangular intermountain basin of 11,668 square kilometres: the Sierra Nevada de Santa Marta, with altitudes above 5,700 metres above sea level (MASL) and climates that vary from humid and snowy to semi-arid temperate; and the Sierra de Perijá, set in climates ranging from cold and humid to warm and semi-humid, with a highest elevation of approximately 3,660 MASL. The sedimentary basin is also a distinct physiographic region, the Cesar-Ranchería Valley; drained by the Cesar and Rancheria rivers which flow through the basin in opposite directions (Figure 1a). The Cesar river flows towards the southwest, being a tributary of the Magdalena river, and the Ranchería river heads northeast and outlets into the Caribbean Sea.

The Cesar-Rancheria Valley has a tropical dry forest biome, the second-most important forest type in the world, covering approximately 42% of tropical and sub-tropical woodland area. The main characteristics of these forests are their deciduousness, a prolonged dry period extending 3–9 months and a high variation of annual precipitation (250–2,000 mm). The forests are unique in nature and provide shelter to a huge number of endemic and endangered species. Among its woody plant species, about 40% are not found anywhere else in the world. These forests are now the most threatened among all forest types worldwide (Hasnat & Hossain 2020). Therefore a proper ecological restoration of the foundations (geomorphology) of the Cerrejón minescapes for this unique biome is a priority.

The Ranchería drainage basin – alluvial plain (Figure 1a) is drained by the Ranchería river, which has a length of 220 km and a drainage basin that covers an area of approximately 4,070 km^2 (Ausenco 2022). It flows down from the Sierra Nevada de Santa Marta to the Caribbean Sea, being mainly fed by streams from the Sierra Nevada and, to a lesser extent, seasonal contributions from streams of the Sierra de Perijá. The mined lands lay at the lower and middle parts of the drainage basin (Martínez Ardila & Vargas Tejedor 2022).

The climatic conditions surrounding the Cerrejón mine (Lower Guajira) are predominantly arid, corresponding to dry and hot climatic regions, although the temperatures are considerably milder than in the northern section of the same Department (Instituto Geográfico Agustín Codazzi [IGAC] 2009; Ausenco 2022). Precipitation concentrates in two rainy seasons, April–May (average of 120–200 mm per month) and October–November (average 100–270 mm per month). The lowest precipitation corresponds to the months of July through February, with the latter sometimes presenting accumulated rainfall values near 0 mm per month (Ausenco 2022).

The Lower Guajira is dominated by plains and hilly landscapes, with piedmont areas transitioning towards the eastern and western margins from where the Sierra de Perijá and Sierra Nevada de Santa Marta mountain ranges rise. These piedmont areas of those mountain ranges present a hilly morphology with gradient slopes ranging from 15° to 30°. The lower, central areas correspond to the alluvial valley of the Ranchería river, characterised by gentle and smooth slope morphologies developed on alluvial materials, and medium and low fluvial terraces made up of quaternary deposits (Figure 1b) (Ausenco 2022).



(a) (b)

Figure 1 (a) The Cesar–Ranchería Valley, showing its key geographical accidents and main coal mines; (b) Geomorphic units surrounding the Cerrejón mine. Information provided by the Colombian Geographic Institute Agustín Codazzi (https://www.igac.gov.co)

The sedimentary rocks underlying the alluvial deposits of the Ranchería Valley correspond to intercalations of sandstone, siltstone, claystone and coal layers (Cerrejón Formation), and the Tabaco Sandstone Formation (Ausenco 2022). Six different soil orders and 14 suborders have been recognised in the La Guajira region. The soil orders are Entisols, Inceptisols, Moltisols, Alfisols, Aridisols and Vertisols (IGAC 2009; Gualdrón

Acosta 2010). Most of the soils affected by mining activity in the Guajira region originated from lateral detrital contributions from hillside areas, as well as sediments from the slopes of the Sierra de Perijá (Gualdrón Acosta 2010).

The biggest mine in this region, which is also the largest in Latin America and one of the largest worldwide, is operated by Carbones del Cerrejón Limited (Glencore). It focuses on extraction, transport, shipment and export of thermal coal. The Cerrejón mining area extends over 50 km in the Ranchería Valley, covering an area of approximately 700 km^2. The presence of coal deposits in the Ranchería Valley has been known since the 15th century. The Cerrejón deposit was first discovered in 1855 and large-scale operations did not start until the 1980s.

3 Methodology

3.1 GeoFluv-Natural Regrade

The GeoFluv-Natural Regrade method is being used to design part of the new rehabilitated and closure landforms of Cerrejón. GeoFluv is a fluvial geomorphic method for land restoration that designs landforms similar to those that naturally would form by fluvial and hillslope processes under the climatic and physiographic conditions at the site. Natural Regrade is the software that aids users to make and evaluate GeoFluv designs in a computer aided design (CAD) format from the input values. The GeoFluv method and related examples have been described elsewhere (Zapico et al. 2018; Bugosh & Epp 2019; Martín Duque et al. 2021a, 2021b) and we refer the reader to them. Suitable and geomorphically stable reference areas need to be identified to provide design input values. For this case a specific analysis of geomorphic natural analogues surrounding the Cerrejón mine is being carried out.

3.2 SIBERIA

SIBERIA is a LEM that has been used extensively by the mining industry for erosion on post-mining landscapes. First used in the 1990s (Willgoose & Riley 1998; Hancock et al. 2008), it provides: (a) visualisation of erosion and where it occurs (i.e. gullies, rills); (b) rates for erosion (t ha^{-1} yr^{-1}) and denudation (mm yr^{-1}). The sediment transport equation of SIBERIA is:

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

where:

q_s (m^3/s/m width)	=	the sediment transport rate per unit width
q_{sf}	=	the fluvial sediment transport term
q_{sd}	=	the diffusive transport term (both m^3/s/m 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:

$$q_{sf} = \beta_1 q^{m1} S^{n1} \tag{2}$$

where:

q	=	the discharge per unit width (m^3/s/m width)
S (metre/metre)	=	the slope in the steepest downslope direction
β_1, m_1 and n_1	=	calibrated parameters.

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

$$Q = \beta_3 A^{m3} \tag{3}$$

where:

β_3 = the run-off rate constant

m_3 = the exponent of area.

Both require calibration for the particular field site.

The model can be run from annual to millennial timescales, but it is mostly run at annual to decadal timescales as it is more convenient to model the average effect of the above processes. SIBERIA describes how the catchment is at any given time based on the parameter inputs. Landscape input is in the form of a digital elevation model (DEM), which is used to determine drainage areas and slope, and, in response to erosion and deposition, adjusts each elevation in the DEM grid. The SIBERIA erosion model has been widely employed for erosion assessment of a range of post-mining landforms (Hancock & Willgoose 2018). A detailed description of SIBERIA can be found in Willgoose (2018). Before SIBERIA can be used, as with all models, parameters for the sediment transport equation (Equation 2) and area-discharge relationship (Equation 3) are required. This parameterisation process is described in detail by Evans (2000) and Hancock et al. (2000).

3.2.1 Parameters – soil

As discussed above, before SIBERIA can be reliably used the model requires input parameters to be determined from site-specific field data. We are currently working on calibrating those parameters for Cerrejón from lidar analysis. Repeated scans are being used to assess type (i.e. rilling, gullying, sheetwash), and differencing one scan from another allows volumetric assessments to be made and erosion rates calculated. These site values are not yet available. Meanwhile, the parameters used here were determined from site materials assuming they have similar properties to other coal mines where the sedimentary geology resembles that of the Cerrejón site. These parameters are available in the SIBERIA database and are derived from the work and data of Sheridan et al. (2000). Here, median erosion parameters are employed; determined from the data set and then adjusted for the increased rainfall at Cerrejón. Refined parameters can be included for later assessments when more data is available. For hillslopes with significant vegetation cover, such as this site, using parameter values would result in a conservative yet high erosion rate. To accommodate this reduction, vegetation cover (C-factors) are available from a range of sources (Wischmeier & Smith 1978; Blanco & Lal 2008). Assuming the vegetation cover is dense, a C-factor of 0.1 has been selected. The SIBERIA β_1 value is then approximated by multiplying the C-factor value to estimate the reduction in erosion based on a constant vegetation cover. The parameters used for the provisional SIBERIA modelling of the geomorphic landform designs of Cerrejón are shown in Table 1. The parameters used here have been validated by comparing existing erosion features (gullies) with that of the model predictions.

Table 1 Parameters employed for the provisional SIBERIA modelling of the Cerrejón mine

	No vegetation cover	Vegetation
β_1	0.0002	0.00002
m_1	1.5	1.5
n_1	2	2
β_3	1	1
m_3	1	1

3.2.2 Landscape and digital elevation model data

Site topography to be modelled with SIBERIA has been obtained from: (a) conventional landforms provided by Cerrejón, and (b) geomorphic design outputs from the Natural Regrade software. The data were exported in .dxf format and converted to ascii text containing coordinate data only. The SIBERIA model requires landscape data to be a re-gridded coordinates input. This irregularly spaced data was then gridded to a variable (depending on the dump's size) regular grid DEM using Kriging.

3.3 Iber

In addition to modelling erosion with SIBERIA, the GLDs for the Cerrejón mine are being subject to hydrologic and hydraulic modelling with Iber. Due to the large size of the mine and its respective WRDs (3–4 km length and up to 100 m height), and even when it was forecasted with SIBERIA that GLD would increase the stability of the new landforms, the main drainage lines would have very high flows. Therefore, they need detailed hydrologic and hydraulic modelling, and, if required, armouring or hydraulic works. Iber (Bladé et al. 2014) is a 2D code that solves the depth-averaged shallow water equations (2D-SWEs) using the finite volume method and the Roe scheme (Bladé et al. 2014). Iber solves the full depth-averaged SWEs in order to compute the water depth and the two horizontal components of the depth-averaged velocity. These equations are solved with an unstructured finite volume solver explicit in time. The algorithms implemented in the model have been extensively validated and applied in previous studies related to river inundation and tidal currents. Iber was originally developed as a numerical tool for flood hazard assessment, risk mapping and sediment transport process in rivers and estuaries (Bladé et al. 2014). Nowadays Iber integrates several calculation modules and capabilities for the numerical modelling of environmental flows (Cea et al. 2016; Ruiz-Villanueva et al. 2019; Sanz-Ramos et al. 2024) and can be also used as a distributed integrated hydrologic-hydraulic model to perform rainfall run-off transformations (Sanz-Ramos et al. 2021).

The analysis of the erosive capability of a rain episode on the GLD of the Cerrejón mine has been performed by analysing the shear stresses produced by rain episodes. According to the mine site requests, precipitation used for modelling are return periods of two and 100 years of one hour of duration. With such criteria, the analysis of the intensity-duration-frequency curve in the Cerrejón mine area leads to consideration of the two precipitation scenarios shown in Table 2. The main purpose of Iber simulations is to obtain the shear stress fields on the terrain surface for each design episode. This variable for the two horizontal components of the shear stress can be calculated:

$$\begin{aligned} \tau_{\mathrm{b,x=}} &= \gamma \cdot h \cdot S_{fx} \\ \tau_{\mathrm{b,y=}} &= \gamma \cdot h \cdot S_{fy} \end{aligned} \tag{4}$$

where γ is the water specific weight and S_{fx} y S_{fy} are the two components of the friction slope calculated with the Manning formula:

$$\begin{aligned} S_{fx} &= \frac{n^2 \cdot u\sqrt{u^2+v^2}}{h^{4/3}} \\ S_{fy} &= \frac{v^2 \cdot u\sqrt{u^2+v^2}}{h^{4/3}} \end{aligned} \tag{5}$$

from *u* and *v,* the two horizontal components of velocity, and water depth *h.* For improved representation, the shear stress is better indicated by means of the critical diameter or the size of the grain of a granular sediment that would be mobilised with such stress, according to Shields (1936) criterion.

4 Results

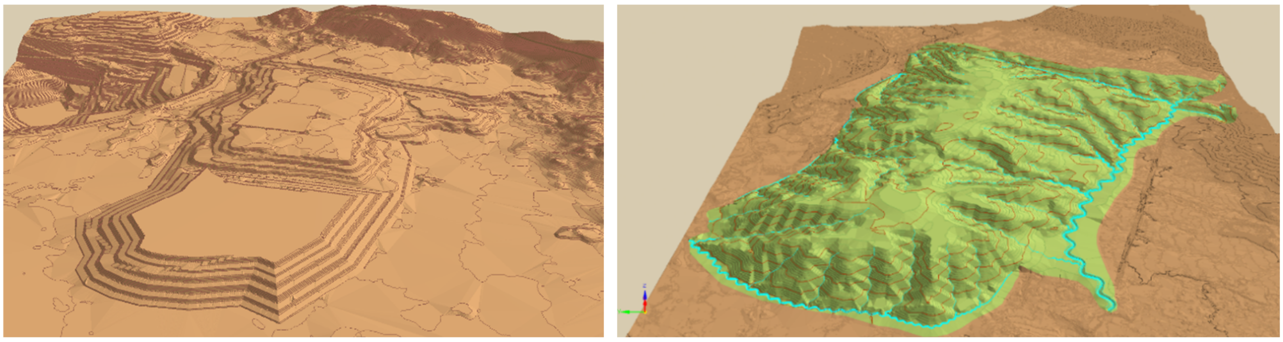
4.1 GeoFluv-Natural Regrade

Table 2 displays a synthesis of the GLD inputs for the Cerrejón mine.

Table 2 Geomorphic design inputs for Cerrejón. * Source of intensity-duration-frequency curve: Maicao Airport, Source: Instituto de Hidrología, Meteorología y Estudios Ambientales (2024)

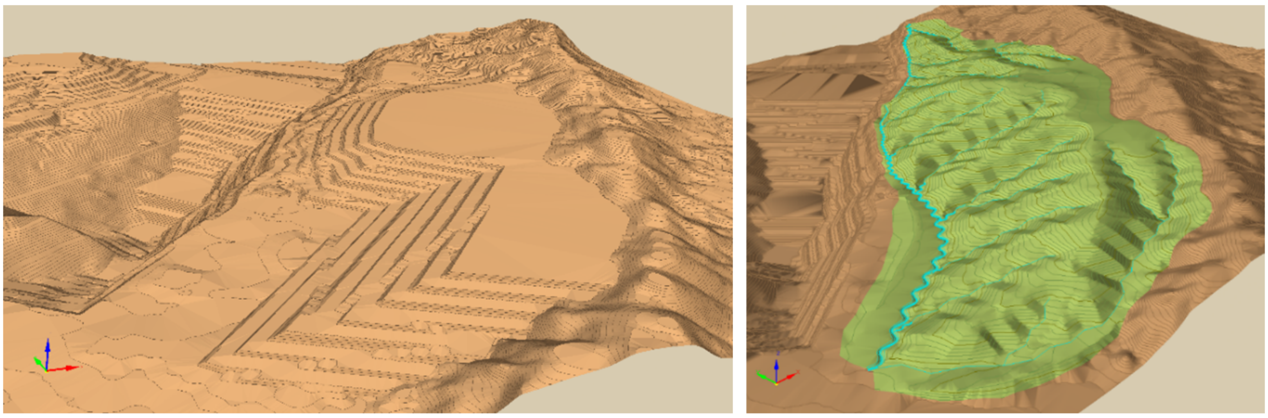
Input	Unit	Value
Drainage density	m ha^{-1}	58.09
Maximum distance from ridgeline to channel's head	m	74.26
Zig-zag channels' sinuosity	dimensionless	1.12
Meandering channels' sinuosity	dimensionless	1.45
2-yr, 1-hr, precipitation *	cm	4.17
100-yr, 1-hr, precipitation *	cm	12.29

Figures 2 and 3 show two examples of the GLD of two large WRDs at the Cerrejón mine: La Estrella (Figure 2), with an area of 1,473 ha and an elevation range between 93 and 230 MASL; and Palmarito (Figure 3), at 634 ha and with an elevation range between 165 and 320 MASL. Both compare with their corresponding conventional topographic designs.



(a) (b)

Figure 2 La Estrella waste rock dump: (a) Initial forecasted life-of-mine topography for the year 2033; (b) 3D view of the geomorphic landform design's proposed alternative topography



(a) (b)

Figure 3 Palmarito waste rock dump: (a) Initial forecasted life-of-mine topography for the year 2033; (b) 3D view of the geomorphic landform design

4.2 SIBERIA

The SIBERIA model was run for the entire landscapes, with sediment free to leave from the DEM boundaries. The simulations yielded erosion rates and maximum depth of gullying for 10, 100 and 300 years for a vegetation cover condition. This may be an optimised outcome as it assumes a complete vegetation cover for the modelled period. Drought, fire and material properties have the potential to reduce vegetation cover. Table 3 presents the results for the SIBERIA modelling of the La Estrella conventional design (life of mine for 2033) at years 10, 100 and 300. Figure 4 offers a visualisation of the year-300 modelling. Table 4 presents the results for the SIBERIA modelling of the La Estrella GLD at years 10, 100 and 300. Figure 5 offers a visualisation of such GLD year-300 modelling.

Table 3 Erosion rates and maximum depths of gullies for the La Estrella conventional design

Year	Max. erosion (gully) depth (m)	Erosion rate (t ha^{-1} yr^{-1})
10	2.59	85.5
100	10.57	85.2
300	14.38	66.1

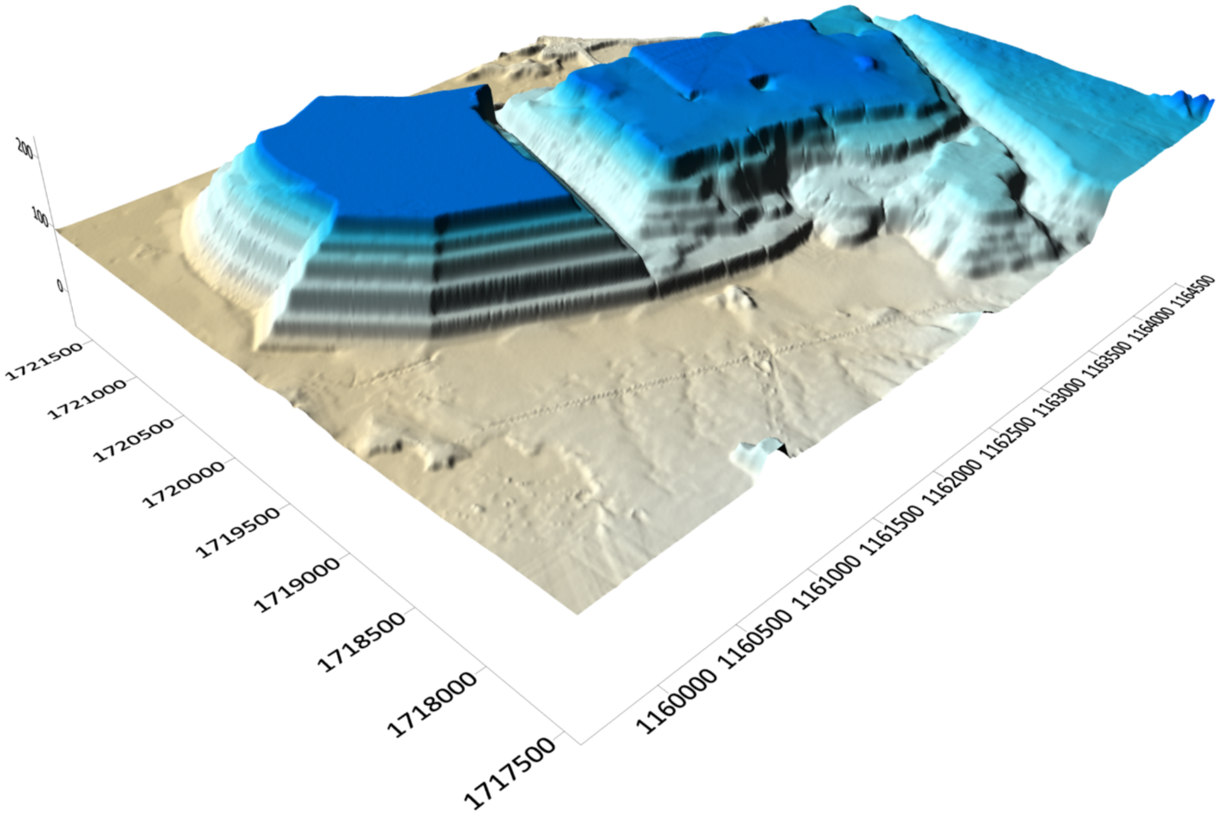


Figure 4 3D view of the La Estrella conventional design at 300 years (vegetation cover). Erosion acts as sheetwash and gullying, although it is difficult to see any major incisions at all at the digital elevation models. The benches of this conventional topography diffuse and merge/erode with the downslope face

Table 4 Erosion rates and maximum depths of gullies for the La Estrella geomorphic landform design

Year	Max. erosion (gully) depth (m)	Erosion rate (t ha^{-1} yr^{-1})
10	1.5	9.6
100	3.1	7.6
300	5.1	6.9

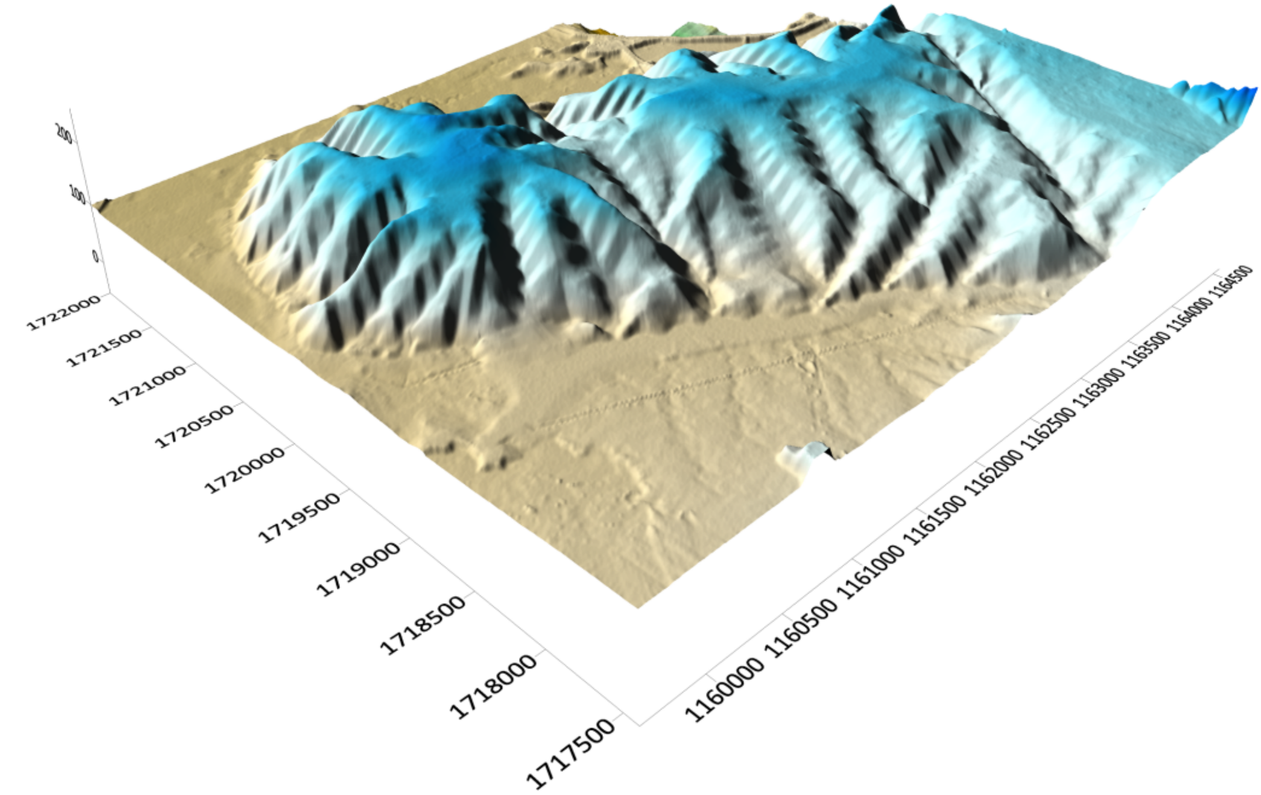


Figure 5 3D view of the La Estrella geomorphic landform design at 300 years (vegetation cover). Erosion acts mostly by sheetwash and has no large gullies. It is difficult to see any major incisions at all at the digital elevation models. We carried out sensitivity studies of the parameters and this landscape is not prone to gullying

4.3 Iber

The process of creating a model to obtain the shear stress or the equivalent parameter of critical dimeter as defined in the Methodology section consists of the following simple steps:

- Generate a triangular irregular mesh of the mine soil surface. To optimise the computational time an irregular mesh has been used, with smaller elements in the watercourses (element size of 2 m) and coarser elements in the hillslopes (element size of 5 m).
- Assign the data precipitation of Table 2 over the whole mesh.
- Execute Iber. The only requirement is to activate the result output of shear stress.

With that, maps of water depths, velocities, shear stresses and critical diameter are being obtained. Results for the two latter parameters in the ordinary episode (T = 2), in this case for the Palmarito WRD, appear in Figure 6.

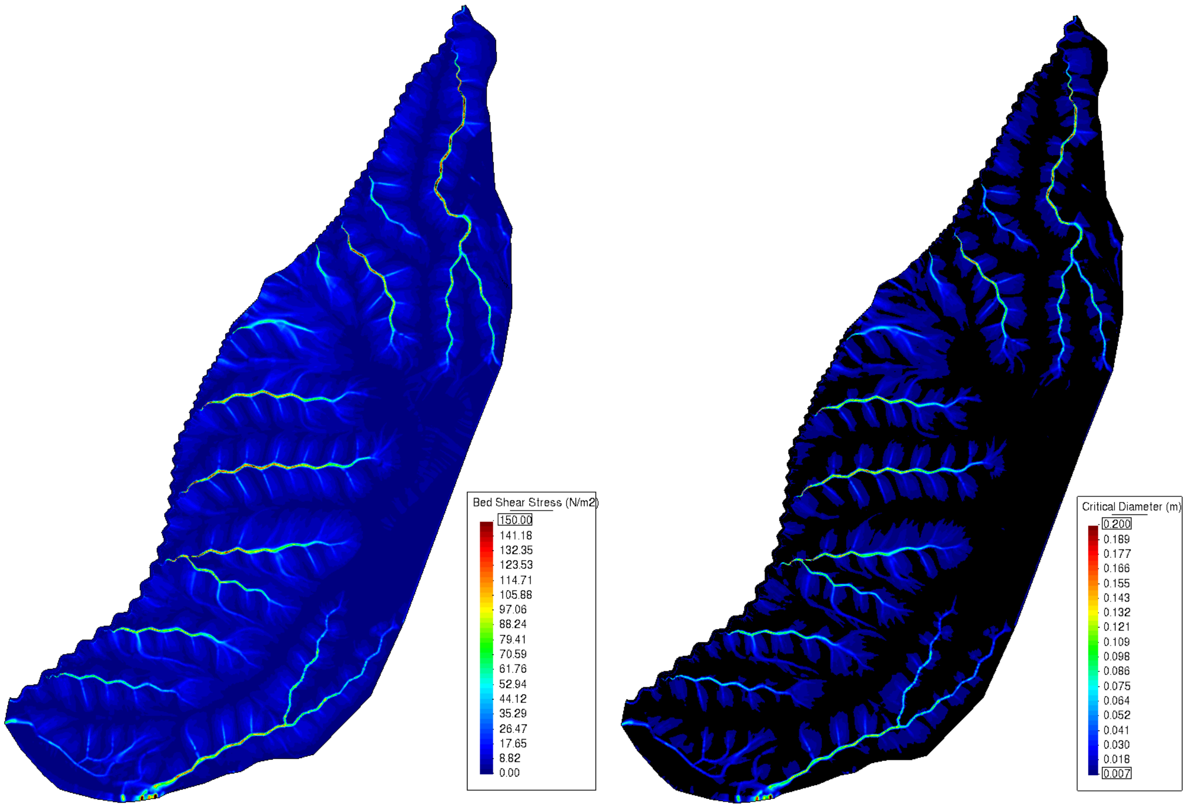


Figure 6 (a) Bed shear stresses and (b) critical diameters for the ordinary (T = 2) episode for the Palmarito waste rock dump. The colour scales have been adjusted to better observe the data in the channels

5 Discussion

5.1 GeoFluv-Natural Regrade

The design process with GeoFluv-Natural Regrade of several WRDs and pits of Cerrejón has demonstrated that the designs are able to store the same volume as their counterpart's conventional designs and have a similar footprint to the conventional life of mine topographies (see Figures 2 and 3). Therefore they do not constrain the volume and area of the operational planning of Cerrejón. With respect to their equivalent conventional benched topographic designs, the geomorphic designs have the following advantages:

- They are predicted to be more erosionally stable, as demonstrated by SIBERIA modelling.
- They blend visually with the natural landscape of the surroundings (see Figures 2 and 3).
- They provide a much more diverse topographic layout than the conventional designs (Figure 7, Table 5), which is the basis for a much higher biodiversity. Topographic diversity improves the opportunities for plants and wildlife. The landform diversity provides variation in gradient, sunlight and shadow from differing slope aspects. This in turn varies moisture retention and, all together, promotes biodiversity.

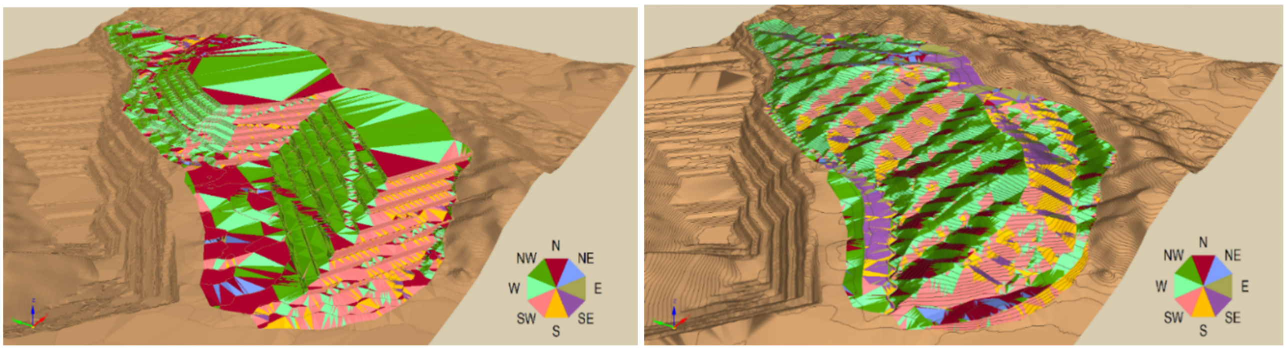


Figure 7 **(a) 3D view of the aspect of the conventional design; (b) 3D view of the aspect of the geomorphic landform design. Notice that the conventional design is dominated by northwest, north and west aspects, whereas the geomorphic landform design has a more even distribution, meaning higher potential for biodiversity. All this is quantified in Table 5**

Table 5 **Comparison of the distribution of the aspect zones between the conventional and geomorphic designs for the Palmarito waste rock dump. Notice a more even distribution for the aspect zones in the geomorphic design**

	Conventional design		Geomorphic design	
Zone	**Surface area (m^2)**	**% of total**	**Surface area**	**% of total**
N	1,406,305.00	22.20	715,295.79	11.29
NE	66,756.12	1.05	368,204.48	5.81
E	10,610.70	0.17	448,456.08	7.08
SE	28,749.51	0.45	601,794.94	9.50
S	150,493.49	2.38	446,485.51	7.05
SW	728,482.47	11.50	802,846.08	12.67
W	1,316,368.57	20.78	1,309,100.14	20.66
NW	2,627,655.20	41.47	1,643,240.60	25.94
TOTAL	6,335,421.06	100	6,335,423.62	100

However, there are also challenges for implementing this new approach at the Cerrejón mine:

- Changing the topography of existing dumps to a geomorphic shape involves large earth movements which may not be efficient. The aim is to evaluate which cases, from an economic and operational point of view, can be subject to geomorphic reshaping, minimising the earth movement at the design.
- Related to the previous point, implementing a geomorphic approach is highly efficient when planned for dumps which are not yet built. This is not easy in Cerrejón, a mine which is at the end of its life. However, it is still possible at some WRDs. In those cases, no extra earth works are involved and therefore the process is efficient. There, a seamless and fluent integration between geomorphic designs and operational planning needs to be made.

5.2 SIBERIA

The model results here used parameters that have been refined by comparison with a limited number of gullies across the site and may not be site-specific for the scope of materials across a WRD. The approach and modelling is preliminary provisional. However, the methods here provide a template for other sites where initial data may be limited. Refinement of the predictions will be achieved with local data as the project evolves. Therefore, the current outcomes should be used more as a guide or as tendencies for the landforms examined. However, since the same parameters have been used for the conventional design and the GLD, there is a basis for analysis and contrast.

The SIBERIA modelling predicts that the geomorphic approach always has less erosion rates than the conventional topographic designs. Of them, we present here La Estrella data, in which the differences between alternative topographies and geomorphic ones are higher. At this site the contrast of results is very significant, with one order of magnitude of difference: 66.1 t ha^{-1} yr^{-1} for conventional topography and 6.9 t ha^{-1} yr^{-1} for the geomorphic proposal, for year 300. We have to stress here that the conventional modelled topography is that left by operation, with outslopes of 1.5H:1V, and not the rehabilitated ones (3H:1V), so that the forecasted erosion for the conventional topography is expected to be significantly lower. The geomorphic designs are prone to some localised gullying in the main drainage lines but this maximum erosion (gully) depth is around one third less than for the conventional alternative.

The forecasted erosion rates of the geomorphic landform designs are lower than what is considered a maximum erosion value for agricultural lands, being 11.2 t ha^{-1} yr^{-1} (Schmidt et al. 1982; Food and Agriculture Organization 1988), and much lower than what is considered by the Queensland Department of Mines and Energy (Queensland Department of Natural Resources, Mines and Water after 2001) as a target erosion rate, i.e. 12-40 t ha^{-1} yr^{-1} for rehabilitated mine sites (Williams 2000). In contrast, the conventional designs offer erosion values above such thresholds. Our interpretation is that the GLD solves the 'spillage' erosion issue by releasing the run-off from the top of the WRDs to their bases, minimising the energy of the run-off and flows since the water is evacuated through sinuous and longitudinally concave existing drainage lines.

In short, the GLD alternative predicted gullying and erosion rates to be relatively low. The design is such that the majority of the hillslope erosion will be captured within the low-slope areas of the catchments. Some gullying is inevitable for any new landform. The location, rate and depth of predicted gullying is typical of that at any new mine and can be managed. In those cases, revegetation and armouring at the channels will mitigate erosion. Rock materials for armouring are availble at the mine. Modelling the use of additional rock armouring, as future work, should also provide useful information.

5.3 Iber

The results from Iber modelling can be used in different ways. On one hand, the more uniform the shear stresses along the channel the better to avoid differential erosions along it. What is shown are the results of the final design of Palmarito, but if there were large differences in shear stresses along the channel, the design could be modified to avoid black spots. On the other hand, the critical diameter results can indicate if erosion will occur or not. If the mean diameter of the soil size is larger than the critical diameter, no erosion should be expected. In cases where the soil grain size is smaller, the results could serve as criteria for gravel or riprap protection of the main channels in order to achieve stability. This is the way in which Iber is being used at Cerrejón to better understand the fluvial erosion processes at the designed channels and to manage such erosion with armouring, or even hydraulic works, if needed.

At the time of writing this paper, Cerrejon is ready to build a small GLD area so that monitoring on it can start as soon as possible, allowing direct erosion measurements to be obtained and compared with both the conventional topographies and with the SIBERIA modelling.

6 Conclusion

GLD and LEMs are relatively well-known and applied in mine rehabilitation and closure in the US, Canada, Australia and some European countries (such as Spain and Sweden). However, they are not yet well-developed in the rest of the world. This paper describes the first use of geomorphic rehabilitation and LEM at the largest open pit mine of South America, Cerrejón (Colombia), for its rehabilitation and closure. The GLD of Cerrejón mine is being introduced without jeopardising the volume of storage or footprint requirements, with forecasted advantages in terms of predicted erosion rates – aiming to avoid 'spillage' erosion processes from platforms and berms — and clear benefits regarding ecological and visual integration with the surroundings. However, some challenges need to be solved, such as minimising earth movements for the reshaping of existing WRDs and achieving a fluent integration between geomorphic designs and mine planning.

The SIBERIA modelling results demonstrate that the geomorphic approach always produces lower erosion rates than the conventional topographic designs. At La Estrella WRD such results are very significant, with one order of magnitude of difference being 66.1 t ha^{-1} yr^{-1} for conventional topography and 6.9 t ha^{-1} yr^{-1} for the geomorphic proposal, for year 300. The geomorphic designs are prone to some localised gullying in the main drainage lines but this maximum erosion (gully) depth is around one third less than for the conventional alternative. However, with the same parameters for both models, the tendencies are clearly favour the geomorphic alternative. In order to better understand this gullying process at the drainage lines, and to avoid it, the GLDs for the Cerrejón mine are being subjected to hydrologic and hydraulic modelling with Iber, a 2D hydraulic model for the simulation of free surface flow in rivers. This allowed us to obtain data on water depths and velocities, bed shear stresses and critical diameters for each drainage line of the GLD. With this information, armouring or hydraulic works are being designed for each drainage line.

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