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Outcomes and lessons learned on the initial application of geomorphic rehabilitation at the Cerrejón mine, Colombia

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Abstract

To support its rehabilitation and closure activities, the Cerrejón mine in Colombia, one of the largest open pit mines in the world, is evaluating the feasibility of applying geomorphic rehabilitation (GR), generally referred to as geomorphic landform design (GLD). The scenarios where GR-GLD has been applied or is being evaluated for implementation at Cerrejón are designing, building and evaluating GLD a pilot project; localised site reshaping of existing waste rock dumps (WRDs) to address gully erosion problems; reshaping existing WRDs to enhance ecological value or to mitigate high visual impact; and incorporating GLD into WRDs that have not yet been constructed. GLD was carried out with GeoFluv-Natural Regrade. To supplement this work, landscape evolution modelling (SIBERIA), hydraulic modelling with Iber (a 2D model for the simulation of free surface flow) and mine planning optimisation (DumpSolver) have been applied to the geomorphic designs. As of June 2026, a 4.8 ha pilot project has been built; 34.8 ha are currently under construction; 2,833 ha were designed both for existing and projected WRDs, and 2,410 ha have been modelled with SIBERIA landform evolution software and Iber hydraulic software. Finally, 34.8 ha have been planned with DumpSolver. The monitoring program has been established but monitoring data from the field are not yet available. The focus of this paper is primarily on the early implementation and feasibility of GLD at Cerrejón.

The pilot project has validated GLD as feasible for integration into mine plans in terms of cost and construction. The main lessons learned from the GLD implementation process were specific training for building GLD is needed for machinery operators; changing deeply embedded earthmoving practices brings some inherent challenges; for implementation at large mines, designs need to accommodate the existing equipment and operational requirements; GLD needs to simplify design outcomes to incorporate planning and building efficiently; as the 'dump to design' comparison demonstrates, GLDs are best constructed from the outset rather than retrofitted – reinforcing the case for early adoption of geomorphic design (new WRDs); and in all cases, GLD needs to incorporate erosional and hydraulic modelling. SIBERIA and Iber were particularly useful for understanding, mapping and quantifying the run-on from the top of the WRD and flows and discharge management at the WRD landscapes.

Keywords: *geomorphic rehabilitation, geomorphic landform design, mine planning, landscape evolution modelling, Cerrejón*

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1 Introduction

1.1 Mine setting

Cerrejón (Glencore, Colombia) is one of the largest open cast coal mines in the world. In 2025, the mine produced 16.8 Mt from 7 different pits, with more than 400 pieces of mining equipment operating. This coal is transported from the mine to Bolivar port, located 150 km northeast of the mine. Bolivar port has been operating since 1985, receiving between 18 and 23 freighters each month. To date, the mine has already rehabilitated more than 5,300 ha. Figure 1 shows the location of the Cerrejón mine and Bolivar port within Colombia’s La Guajira department. The mine is located within the Ranchería River drainage basin.

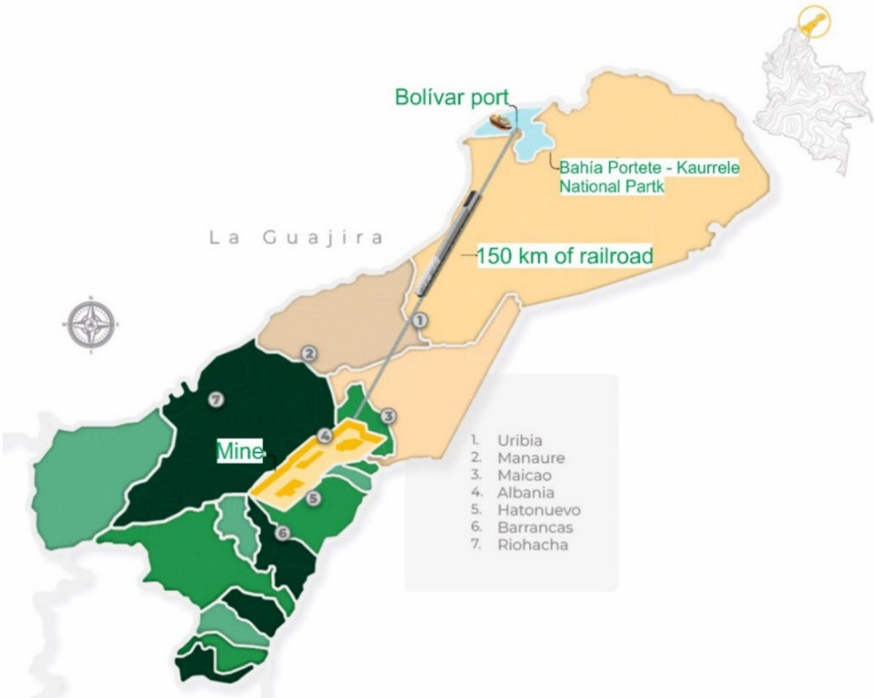


Figure 1 Location of the Cerrejón mine

1.2 Current landform rehabilitation practice, run-off management and challenges

Currently, landform construction at Cerrejón manages several interacting factors to deal with tropical rain events, weathered material and a stepped berm-batter topography, with lifts 20 m of height. Soil erosion and run-off management are the main environmental challenges faced in terms of mine rehabilitation. The landform design commences with transforming, by dozing, the angle of repose (approximately 37°, 75%, 3 V:4H), resulting of direct dumping of the WRD, into outslopes of 18.4° (33%, 1 V:3H), leaving 60 m-wide platforms (corridors), which include perimeter bunds to control run-off. The rehabilitated surfaces are covered with 30 cm of topsoil and then vegetated. Surface run-off is managed via concrete drop-down structures connected to sediment ponds and discharge channels (Figure 2).

The Rational Method is used for flow estimations, with return periods of 10 years for hydraulics (precipitation of 70 mm, 10 years annual recurrence interval (ARI), 60 minutes’ duration, according to intensity-duration-frequency (IDF) data from the Intercor camp’s weather station) and 20 years for sediment transport. The maximum water velocities used for design are 1.5 m/s in channels and 5 m/s in structures.

The drop-down structures are expensive to both construct and maintain, and surface run-off often develops alternative flow paths, resulting in major gully development. In addition, the use of concrete in a natural environment should be minimised. Therefore, Cerrejón is seeking more efficient, cost-effective and environmentally friendly alternatives for run-off management, for which GLD is emerging as an option with promising potential.

Figure 2 Current run-off management at Cerrejón consists of a network of concrete drop-down structures connected to sediment ponds linked to the fluvial network through discharge channels

2 Objectives

Martín Duque et al. (2024) described the initial steps for the introduction of geomorphic rehabilitation, supported by landscape evolution and hydraulic modelling at Cerrejón. At that time (2024), geomorphic rehabilitation was in a design state. To date, some GLDs have been built (totally or partially), with others planned for future construction, and the objective of this paper is to describe the outcomes and lessons learned from this recent experience. More specifically, our recent work has tested pilot constructability incorporating local planning and equipment, mine planning staff, cost comparisons, together with revealing the challenges likely in full-scale implementation. Evaluating erosional performance via monitoring is the next step for these sites.

3 Methodology

The GeoFluv-Natural Regrade method has been used for design of the geomorphic rehabilitated and closure landforms at Cerrejón. GeoFluv is a fluvial geomorphic method for land restoration that designs landforms similar to those that formed by natural 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 (Bugosh & Epp 2019; Martín Duque et al. 2021 a, 2021b). 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 near the Cerrejón mine has been carried out. The geomorphic design inputs for Cerrejón were published in Martín Duque et al. (2024) with drainage density found to be 58.1 m/ha. The run-off coefficient for the WRDs is 0.52, according to internal Cerrejón reports.

Recognising the difference in materials from the natural analogues and the mine wastes, the stability performance of the GeoFuv-Natural Regrade landform designs for Cerrejón has been erosionally modelled with SIBERIA. SIBERIA is a landscape evolution modelling software that has been used extensively by the mining industry, mostly in Australia, for erosion on post-mining landscapes. First used in the 1990s (Willgoose & Riley 1998; Hancock & Willgoose, 2018), it provides visualisation of erosion and where it occurs (i.e. gullies, rills), and rates for erosion (t/ha/yr) and denudation (mm/yr). Flume testing of materials, or other calibration procedures, could not be carried out, so that erosion parameters were derived both from sites with similar material (Hancock et al. 2008) and from unpublished erosional reports by carried out Cerrejón.

In addition to the long-term erosion modelling with SIBERIA, the GLDs for the Cerrejón mine were subject to hydrologic and hydraulic modelling with Iber. Due to the large size of the mine and the WRDs, the main drainage lines will have high flows that need detailed hydrologic and hydraulic modelling. Armouring or hydraulic works may also be required. 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).

DumpSolver (formed in 2002) provides a landform design service via software and analytical tools and methods to control and logically minimise construction cost while maintaining the required construction and closure requirements for mine landforms. The process works on the principle of direct integration of costs in the mining plan, so a quality environmental outcome is achieved. After primary mining, the rehabilitation of an existing slope presents several challenges, including safety, construction access and sequencing, materials movement and reshaping economics. DumpSolver developed a staged approach to evaluate waste rock landforms at all stages of the life cycle, from concept and feasibility through operation, rehabilitation, closure and relinquishment of the landforms. DumpSolver was used to provide the mine planning for the implementation of the geomorphic designs.

4 Results and discussion of implementing geomorphic landform design at Cerrejón

The Cerrejón mine has been in operation for decades and has already rehabilitated more than 5,300 ha. Therefore, the opportunities for integrating geomorphic rehabilitation early are limited, but GLD still has a high potential for beneficial implementation across Cerrejón. The 4 scenarios and situations in which GLD is either being introduced, evaluated or considered for enhancing rehabilitation and closure of Cerrejón are:

- Scenario 1: a pilot project
- Scenario 2: locations in which the conventional solutions of rehabilitation and water management failed
- Scenario 3: places of either high ecological value or landscape sensitivity
- Scenario 4: new WRD to be built, so that GLD could be introduced from the beginning.

These are described below.

4.1 Scenario 1: testing geomorphic landform design at the Annex waste rock dump pilot project

Cerrejón started the application of geomorphic rehabilitation through a pilot project at its Annex waste rock dump. The pilot project was designed and built so that a small-scale case study could be used to evaluate the feasibility, time, cost and potential risks of the application of GLD in landform construction, well before full-scale implementation is considered across the mine. By building a pilot geomorphic landform, the company can test the operational feasibility of this new landform solution, and commence monitoring the performance of these new geomorphology-based rehabilitated area. The GLD was designed between June and July 2025. It covered an area of 4.8 ha, including 80,000 m^3 of material movement (balanced cut-and-fill). Its location, adjacent to natural areas, provided the opportunity to maximise the integration and blending in with the surrounding terrain, complementing its natural drainage pattern. Figures 3–5 show the pilot project once built, in the vicinity of a conventional landform (outslope-berm) rehabilitation. The construction of this pilot project demonstrated its feasibility. However, the company requested that specific training be provided for the machinery operators, as the designs would require adaptation for use with large equipment. We also learned that there were inherent challenges in changing deeply embedded earthmoving practices.

Performance monitoring of the pilot project will provide ongoing evaluation of the design. To date, only post-storm inspections and maintenance tracking have been undertaken (Figure 4). However, monitoring will be completed by way of repeated drone/lidar surveys, gully mapping, sediment monitoring, soil development, vegetation establishment and surface stability analysis. This monitoring is in a very early stage and results are not yet available.

Figure 3 Aerial view of the geomorphic rehabilitation pilot area of the Annex waste rock dump, showing the traditional, benched landform design in the background. Image taken on 25 December 2025

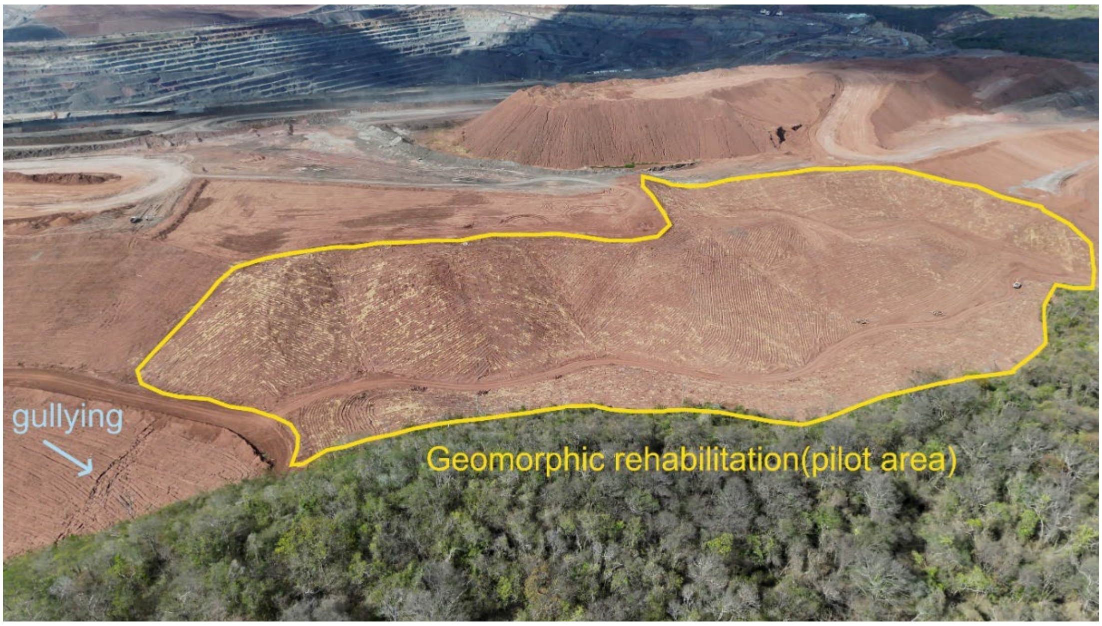


Figure 4 Aerial view of the geomorphic rehabilitation pilot project of the Annex WRD, noting the occurrence of gullying in the conventional landform design. Image taken on 26 January 2026

(a) (b)

Figure 5 (a) Geomorphic rehabilitation pilot project in January 2026; (b) Drainage channel armouring (white lines)

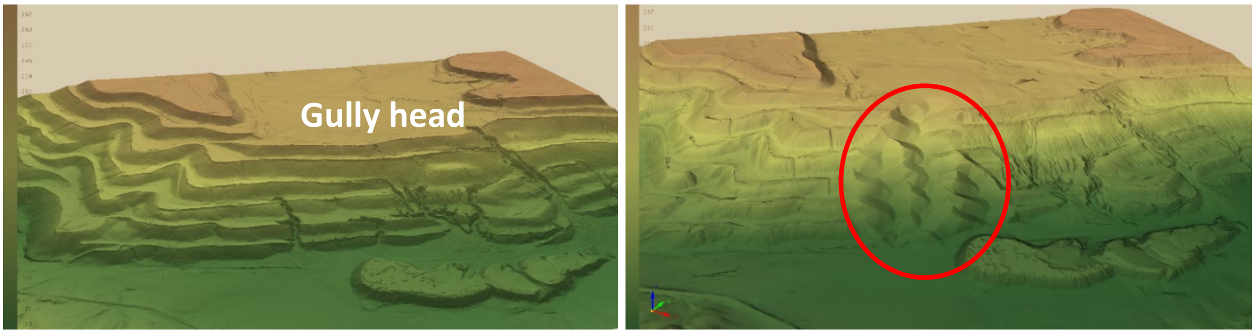
To the authors' knowledge, the pilot project at the Annex WRD is the first geomorphic rehabilitation example in Latin America (South and Central America) and the first geomorphic rehabilitation example in a tropical climate worldwide. Therefore, the evaluation of its erosional performance will make a valuable contribution to the development of geomorphic solutions to mining in this region. We reinforce that we are describing the application of specific techniques outlined and applied through the application of geomorphic rehabilitation, or GLD. We refer to methods and techniques well established and recognised in both the scientific and technical literature (see Martín Duque & Lacy, 2025). We must make this point since it has become common practice, unfortunately, to see practitioners or companies claim that they use geomorphic rehabilitation by simply 'twisting straight lines' in CAD.

4.2 Scenario 2: healing large gullies at the Potrerito waste rock dump

At the Potrerito WRD, deviations from high-quality standards of conventional rehabilitation led to formation of large gully erosion at some locations. Rather than infilling and armouring them – the typical industry response – Cerrejón is geomorphically reshaping these gullies, supported by channel armouring, understanding that they are already functional drainage lines, and assisting them to work towards (dynamic) equilibrium. Figure 6 shows the comparison between the existing topography and a proposed GLD solution to a sector of the hillslope, from the top to the bottom of the WRD. Figure 7 illustrates reshaping of an existing large gully underway.

Specifically, the stabilisation approach consists in 'fitting' GeoFluv-Natural Regrade geomorphic designs into existing gullies to achieve the following:

- transforming the channel geometry from straight (in plan view and longitudinal profile) into a zigzag plan view pattern and concave longitudinal profile
- transforming the vertical gully walls into smooth scalloped, convex-concave, hillslopes
- linking the base level of the channels to stable positions of the WRD foot perimeter channels
- designing appropriate armouring according to shear stress and equivalent size diameter hydraulic modelling with the Iber software (see Section 5.2 and Martín Duque et al. 2024).



(a) (b)

Figure 6 (a) 3D view of the Potrerito waste rock dump without any geomorphic landform design or reshaping; (b) Proposal for geomorphically reshaping one sector of the Potrerito waste rock dump (red ellipse)

(a) (b)

Figure 7 (a) Large gully at the Potrerito waste rock dump, formed by the overtopping of the dump's upper surface (gully head also shown in Figure 6a); (b) Initial geomorphic reshaping

4.3 Scenario 3: retrofitting a geomorphic design into existing waste rock dump

4.3.1 Applying DumpSolver to the 'as dumped' Tipiala waste landform

A sector of the Tipiala waste landform has been geomorphically designed to enhance ecological value; 49.6 ha of the Tipiala WRD has been designed to GLD. This area comprised run of mine coal mine waste dumped on a plateau which abuts the surrounding forested area adjacent to the mine. The landform has an overall plan length of approximately 1,350 m, with a slope length of approximately 400 m. The waste material was end-tipped in the standard manner in 3–4 lifts of varying height (Figure 8). For this structure of variable surfaces, a GLD was developed. The design drains the slopes of the landform to a series of contained ponds between the toe of the landform and the forest (Figure 8). This example illustrates one of the situations in which GLD adds value to the mine rehabilitation and closure of Cerrejón, delivering landscapes which are not only more erosionally stable, but that they have higher capabilities as habitats. This GLD case is currently under construction (Figure 9).

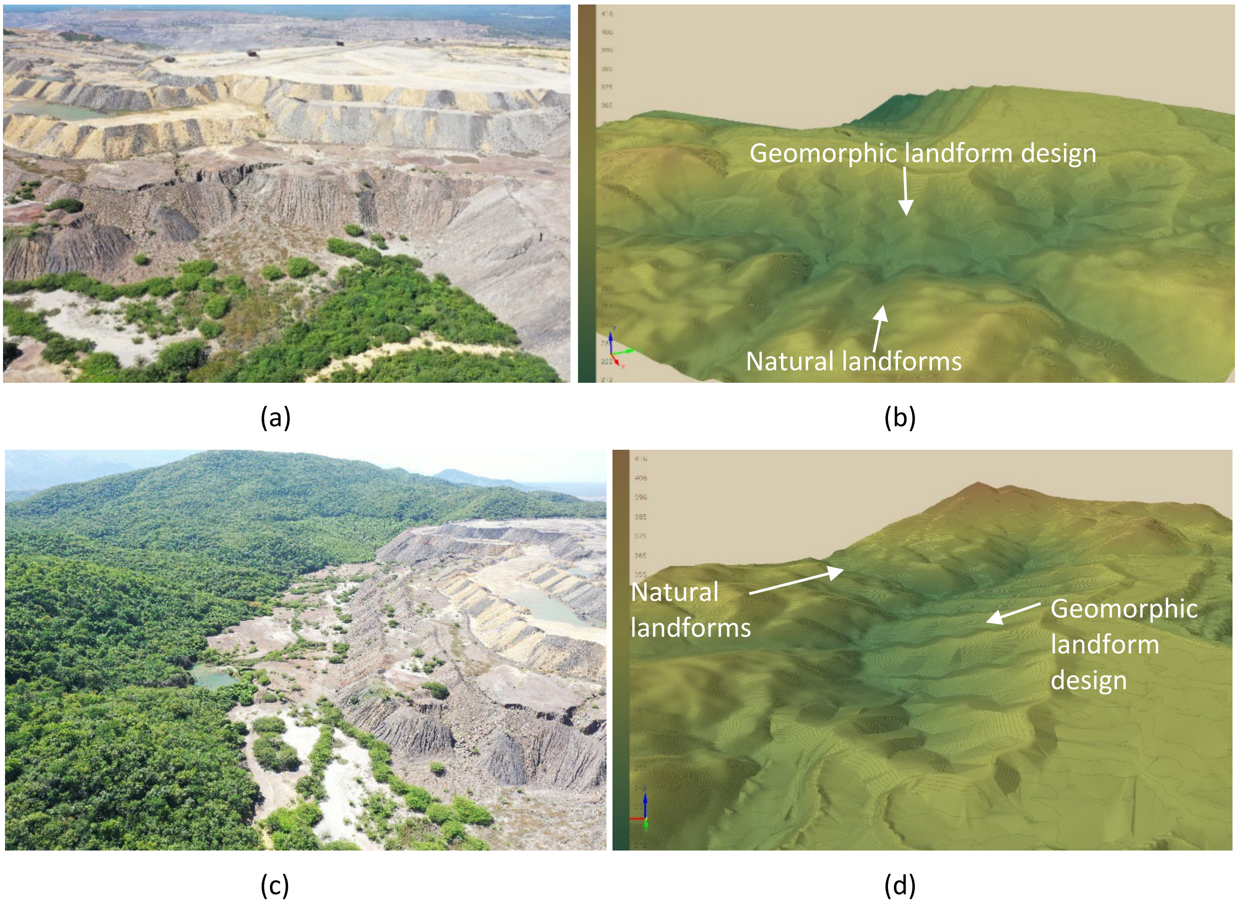


Figure 8 **(a) and (c) Tipiala existing landforms, as dumped; (b) and (d) 3D views of digital elevations models of the geomorphic landform design, blending with the natural landforms of the surroundings**

Figure 9 **Tipiala ('Jaguar') geomorphic landform design scenario under construction (May of 2026) showing lifts being reshaped into 'natural' landforms. See Figure 8c for comparison and Figure 10 for the design**

4.3.2 Evaluation and approach

The desktop task was to evaluate and reshape the existing 'as dumped' Tipiala landform into the geomorphic landform and provide a staged/scheduled mining plan, to deliver an efficient and economical transformation of the current Tipiala waste dump.

Moving the 'as dumped' material of the existing structure and adopting the geomorphic design required additional material movement for various purposes, particularly as a shallower outer face equates to longer dozer pushes. There were 3 key considerations for approaching the task:

- Dozing: for rehabilitation tasks, the most efficient equipment is a dozer, dozing down dip, followed by lateral dozing if required.
- Management panels: a series of lateral compartments were used to define rehabilitation areas. This approach demarcated the lateral extent to which dozing is efficient. At Tipiala, the lateral panel extent is defined by the ridges and watercourses of the provided geomorphic design; 16 panels were used.
- Haulage: inter-panel haulage is conducted using earthmoving equipment, either via a truck fleet (requiring ancillary equipment) or a scraper. The material type, haulage distance and equipment availability will determine the optimal method.

There are 3 compounding factors when considering the required relocation of waste for reshaping a waste landform, considered on a local and site-wide scale:

- volume to be relocated
- distance to be moved
- orientation of material movement: laterally, up slope or down slope (or some combination of all 3).

The gross volumes and the size of the site, along and down slope, will generally control the size and nature of the equipment best suited for the task.

4.3.3 Mine planning results

Most of the benches of the landform feature a mix of cut-and-fill. The results provided a gross cut-to-fill balance with a cut volume of 1.404 Mm^3. When considered over the total project, the total movement by down slope dozing within panels is 272,000 m^3 or 23% of the required movement, and the slope dozing distance is a weighted average distance of 85 m.

By removing the internally dozed material from the evaluation, we can extract the material that needs to be moved by load and haul as cut-to-fill.

For the waste that needs to be moved between panels, as inter-panel waste movement – the load and haul volume is 467,804 m^3. Once the load and haul is completed in a panel, bulk dozing can commence, a process that needs to be completed to a high degree of accuracy, using experienced operators with high-quality GPS-guided machines and skills well above those typically used during normal waste dumping. Smaller dozers are required for finishing the bulk dozing to the required detail, with experienced operators having final cut skills.

In summary, this analysis yielded the feasibility for retrofitting a GLD to the Tipiala-Jaguar waste landform. Construction of this project started in May 2026 (Figure 9).

4.4 Scenario 4: providing a 'dump to design' comparison

4.4.1 Tipiala constructed to geomorphic design: an activity comparison

Cerrejón requested that we develop an understanding of the economic impact if a well-executed GLD had been applied initially for the Tipiala-Jaguar waste landform, in order to evaluate its potential for other WRDs to be built. For this purpose, the retrospective design, previously described (Section 4.1) is compared, and primarily relates to the bulk dozing down the Tipiala landform hypothetically dumped to its geomorphic design footprint, with the tipped faces then regraded to the GLD final slope configuration. Figure 10 shows the Tipiala GLD that provided the 3D surfaces to conduct the 'retrofit to design' and for the 'dump to design' programs.

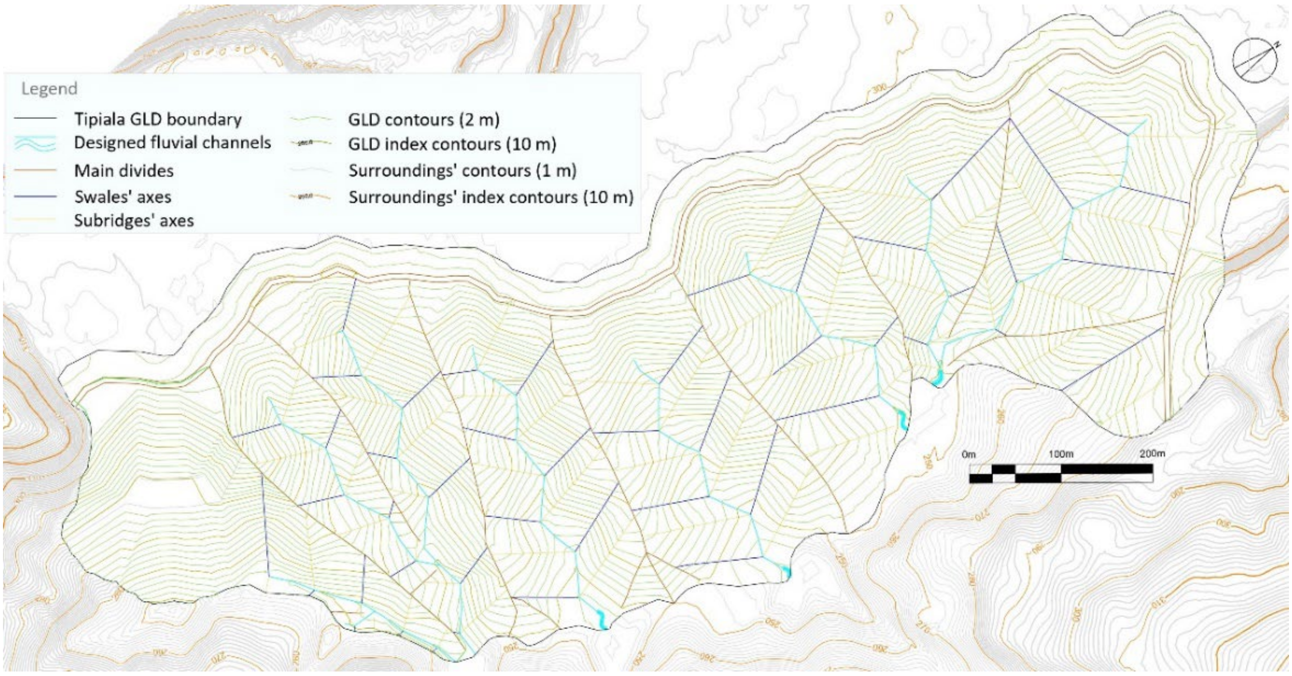


Figure 10 Tipiala geomorphic landform design. See Figures 8 and 9 to compare with the starting surface, 3D views of the geomorphic landform design and current construction

Another major design consideration is the WRD bench height. To test this, we compared the regrading of the standard 20 m-high bench (applied at Cerrejón) with a 10 m bench height. Larger trucks generally use higher tip heads because this allows slower tip head advance rate, easier/less equipment required for tip head clean-up, and fewer tip head roads; however, it would be possible to complete 10 m tip heads for the final approach to the final tip head, particularly if cost savings can be attained. A comparison was therefore performed.

4.4.2 Evaluation and approach

Once primary dumping of waste is completed, the remaining tasks in waste landform construction and completion are generally:

1. Bulk reshaping of the bench face to a final profile.
2. Topsoil placement, spreading over the final surface to the designed depth.
3. Placement of water control structures.
4. Ripping (in some circumstances) and seeding/planting of seedlings.

Tasks 2 and 4 are common to both scenarios and can be discounted from this comparative analysis; Task 3 is common in conventional rehabilitation, which for GLD is substituted by channel armouring (cheaper and better for ecology). However, we did not undertake such comparison. Therefore, our analysis is based purely on a comparison of Task 1. Bulk reshaping to the final profile between the current stepped landform designs and a geomorphic 'as dumped' landform design. The most significant impact of building to a GLD compared to retrofitting is the avoidance of the need to load and haul waste. This is major cost associated with not dumping to a GLD design (Section 4.3) as there would likely be little to no load and haul prior to developing the final geomorphic reshaping landforms (Task 1).

The primary task after tipping the waste to the GLD is to reshape the bench to the rehabilitated slope. By taking the mid-bench contours, we obtain the crossover point across the entire bench. However, as expected from the GLD methodology, the slope above and below the mid-bench contour varies down and across a slope. Points are sampled along the design slope to cover the entire face of the reprofiled landform. Using dozer slope evaluation, balanced cut-to-fill and evaluating geometric areas and distances, we can draw comparisons between 10 m and 20 m bench heights. However, it needs to be acknowledged that construction of more benches will see an increase in dumping costs and may require higher dozer expenses pushing dirt when the dumps are being constructed.

4.4.3 Mine planning results – DumpSolver-derived comparisons

To compare the 'retrofitted' (Section 4) to 'dump to design' (Section 5) scenarios, we converted all activities to D9-equivalent dozing hours. This method was chosen in preference to a unit of currency since mines can have very different cost structures and the intent was to illustrate comparative value.

To retrofit a GLD to the as-dumped Tipiala landform, we estimated that the bulk dozing for a D9 took 2,011 hours, from the current Tipiala structure (20 m lifts) to the final rehabilitation surface. Additionally, the load and haul component required 4,638 equivalent D9 hours, giving a project total of 6,649 equivalent D9 hours (Table 1).

For the 'dump to design' scenario, it was estimated that dozing requirements for a D9 were 1,708 hours with a Tipiala bench structure of 20 m, and if it was dumped to the geomorphic design and regraded to a final rehabilitation surface. This is a 74% reduction in the total cost compared with a retrofitting the design to the landform.

The 'dump to design' comparisons of lift height, i.e. reducing the dump bench lift height from 20 to 10 m, and subsequent bulk regrading resulted in a considerable reduction in bulk dozing requirements, from 1,708 D9 hours to 586, a reduction of 1,122 hours, or 66%.

Table 1 Retrofitted versus dump to design with bench height comparison (*D9 hours)

Using a 20 m-high bench (costs)	Using a 10 m-high bench (costs)
Retrofitted - 6,649 hours	Retrofitted - 6,649 hours
Dump to design - 1,708 hours	Dump to design - 586 hours
Savings 4,942* hours (74%)	Savings 6,063* hours (91%)

In summary, adopting a GLD from the start of the dump creation, rather than attempting to retrofit an existing dump, has significant cost savings. The selection of the optimal dump bench lift height can also deliver additional cost benefits.

For the Tipiala-Jaguar waste landform, in D9 equivalent hours, the study shows that by adopting the GLD from the commencement of dumping:

- Bulk lateral movement (load and haul) can be avoided, removing 4,638 hours of D9 equivalent cost.
- In a 'dump to design' with 20 m lifts, 303 hours of bulk dozing are saved in regrading.
- In a 'dump to design' reducing tip face height to 10 m lifts, a further 1,122 hours of bulk dozing is saved.

The latter 2 points affirm that there can be further savings by optimising the dump bench lift height.

Hence, for the 1.3 Mm^3 tonnes Tipiala-Jaguar waste landform in 10 m lifts, an equivalent of 6,063 D9 hours or 91% would have been saved by building the landform to the GLD in comparison to regrading a conventionally dumped design and retrofitting that structure. Again, we need to stress that there would be additional costs in constructing more benches.

Overall, an optimal landform design would look to adopt a GLD initially – as the studies clearly demonstrate the advantages of constructing GLDs rather than retrofitting an established dump.

5 Results and discussion of erosional and hydraulic modelling

5.1 Erosional modelling – SIBERIA

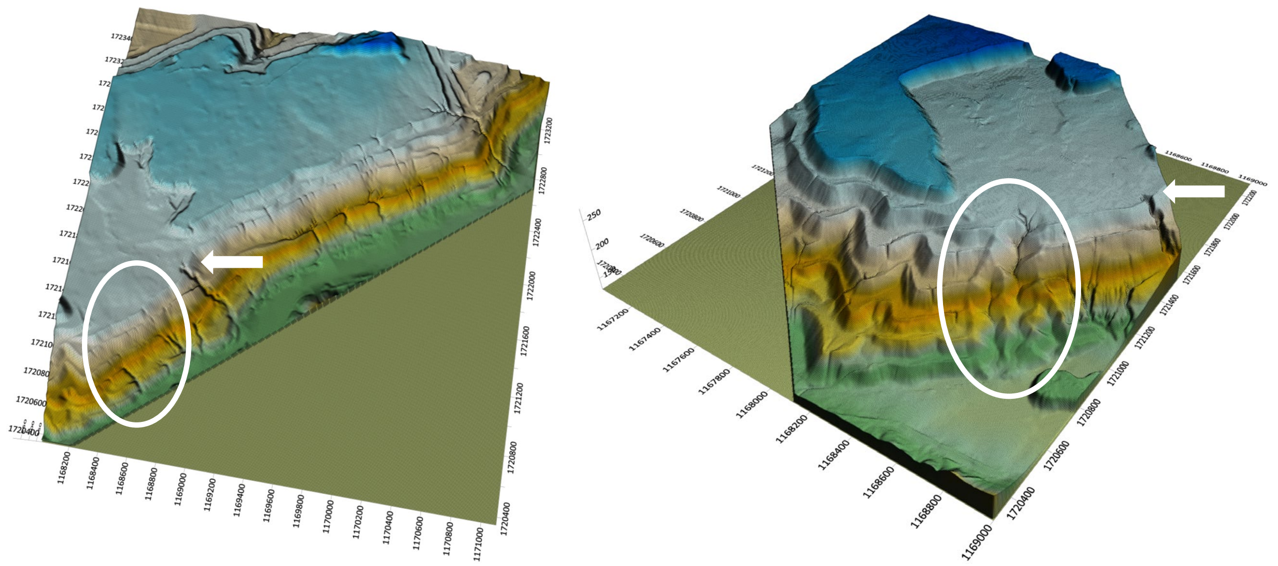
SIBERIA modelling at Cerrejón is detailed in Martín Duque et al. (2024) where we included the erosional forecast for large WRDs such as La Estrella or Palmarito. Since this paper, we have modelled new scenarios, such as the GLD of Annex (pilot project), Potrerito or Tipiala WRDs, described above, consistently using the same parameters (Table 2). Those parameters are for the vegetation assumption of 'vegetation cover', since Cerrejón has proven success in establishing vegetation covers at the WRD. In all the cases, modelling compared conventional landform designs with GLD alternatives, consistently forecasting significantly lower erosion rates for the latter. A key finding is that SIBERIA predicts gully formation in locations that do not coincide with engineered drop-down positions – therefore, the SIBERIA modelling it could be used to optimise their placement. Furthermore, when an initial drainage pattern is imposed through GLD, the erosion system becomes more predictable and controllable. While some localised gullying is expected along primary drainage lines, maximum gully depth is approximately one-third less for GLD than for conventional designs and can be managed through targeted armouring. This pattern is also consistent in the new modelling. Table 3 and Figure 11 show the comparison of conventional and GLD erosion outputs for one sector of Potrerito WRD. A useful learning of this modelling was understanding that the run-off entering the head of the GLD, draining the large upper (flat) surface, is the most vulnerable point in the design. This learning is helping Cerrejón avoid this risk by designing specific hydraulic works that connect upper surface run-off into the entry point of the GLD solution.

Table 2 Parameters employed for SIBERIA modelling at Potrerito waste rock dump

	Vegetation cover
β1	0.00002
m1	1.5
n1	2
β 3	1
m3	1

Table 3 Erosion rates and deposition and gully depths for the Potrerito waste rock dump, comparing conventional and geomorphic landform design alternatives

Year	Conventional landform design			Geomorphic landform design		
	Min. depth (m) (deposition)	Max. depth (m) (gully)	Erosion rate (m^3/ha/yr)	Min. depth (m) (deposition)	Max. depth (m) (gully)	Erosion rate (m^3/ha/yr)
10	1.02	1.18	7.0	0.27	0.45	5.3
100	4.10	13.7	7.7	0.80	2.45	5.3
300	4.19	19.22	8.2	0.92	6.49	5.9

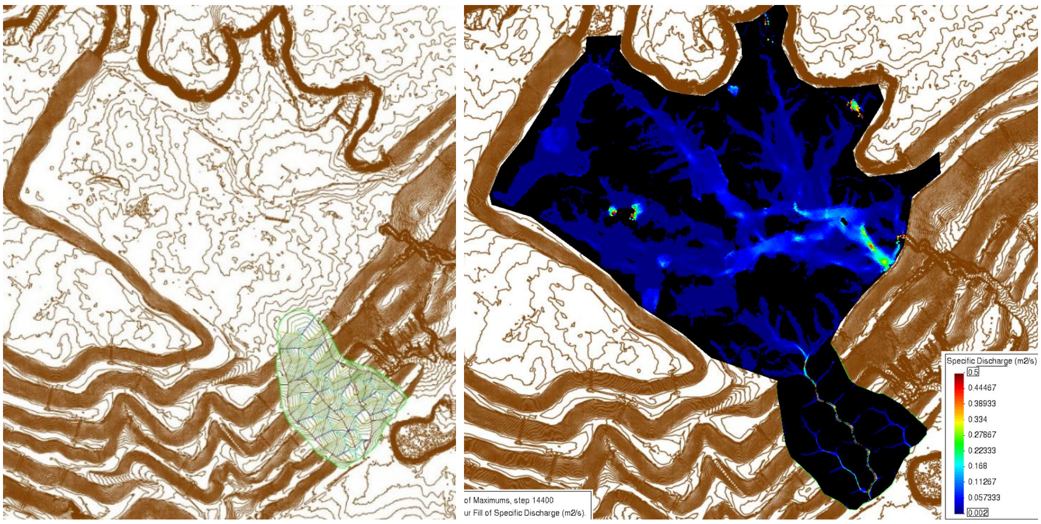


(a) (b)

Figure 11 3D view of the Potrerito waste rock dump SIBERIA modelling at 300 years; (a) Current conventional topography (whole dump); (b) Geomorphic landform design at a specific sector. The position of the large gully, also shown in Figures 6 and 7, is indicated with an arrow, to show location. The white ellipse shows the position of the geomorphic landform design

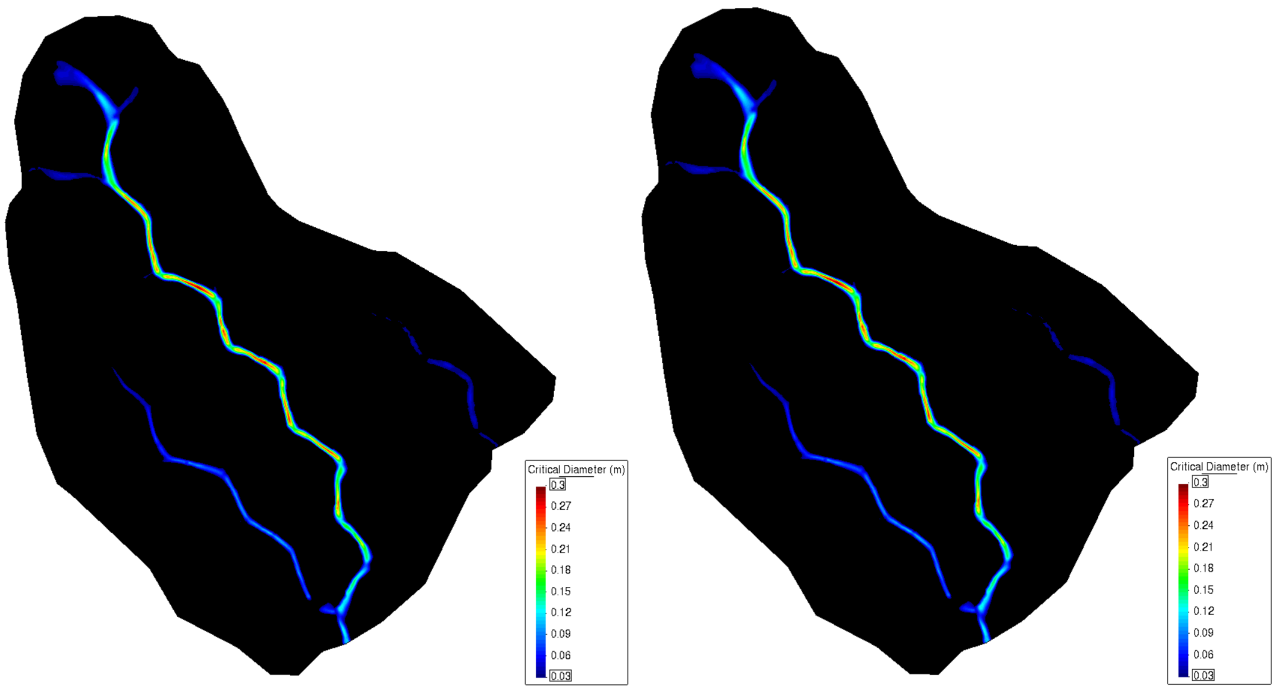
5.2 Hydraulic modelling – Iber

In addition to SIBERIA, every GLD developed for Cerrejón has been also subject to hydraulic modelling with Iber (Bladé et al., 2014), producing maps of water depths, velocities, specific discharges, discharges, shear stresses and critical diameter for each design. As an example, we include here results of specific discharge, shear stress and critical diameter of armouring for the Potrerito WRD (Figures 12 and 13). The design storm corresponds to a return period of 100 years and 1-hour duration, which is 122.9 mm/h, according to local IDF data. Figure 12 shows the modelling of the Potrerito GLD, including the additional watershed of the WRD. The modelling reveals that most of the run-on discharge of this area (2.25 m^3/s) enters the large existing gully (Figure 7a), whereas the GLD area receives only 0.74 m^3/s, which will be handled with a drop-down structure connecting the large upper (flat) surface of the WRD and the GLD.



(a) (b)

Figure 12 (a) Geomorphic landform design of a sector of the Potrerito waste rock dump; (b) Specific discharge (m^2/s) modelling with Iber



(a) (b)

Figure 13 (a) Bed shear stresses; (b) Critical diameters for the extraordinary (T = 100) episode for the Potrerito geomorphic landform design. The colour scales have been adjusted to better observe the data in the channels

6 Conclusion

Cerrejón is seeking an efficient, cost-effective and environmentally friendly alternative for soil erosion control and run-off management, for which GLD is emerging as an option with promising potential. Soil erosion performance and economic savings of GLD solutions are currently under analysis.

The scenarios where GR-GLD has either being implemented or is being evaluated for implementation at Cerrejón are designing, building and evaluating a GLD pilot project; localised site reshaping of existing WRDs to address gully erosion problems; reshaping existing WRDs to enhance ecological value or in areas of potential high visual impact; and incorporating GLD into WRDs that have not yet been constructed. Of these GLD activities, as of June 2026, 4.8 ha have been built at the pilot project, 34.8 ha are currently under construction, and 2,833 ha were designed both for existing and projected WRDs. An extensive independent assessment has been conducted with 2,410 ha modelled with SIBERIA and Iber, and 34.8 ha have been planned with DumpSolver. The monitoring programs are still being established, and monitoring data are therefore not yet available.

The outcome of the pilot project validated GLD as a feasible approach in terms of cost, construction and integration into mine plans. The main lessons learned were that specific training for building GLD is needed for machinery operators; it is inherently difficult to change deeply embedded earthmoving practices; for implementation at large mines, designs need to accommodate larger equipment and operational requirements; GLD needs to simplify design outcomes to incorporate planning and building efficiently; GLDs are best constructed from the outset rather than retrofitted – reinforcing the case for early adoption of GLD at Cerrejón where it is still possible (new WRDs); and GLD needs to incorporate erosional and hydraulic modelling – SIBERIA and Iber were particularly useful understanding, mapping and quantifying the run-on from the top of the WRD and flows and discharge management at the WRD landscapes.

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