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Completion and monitoring of the geomorphic-based LIFE RIBERMINE project: transference to other abandoned mines

José Francisco Martín Duque [a,*], María Tejedor [a], Paul Royal [b], Cristina Martín-Moreno [a], Gregory Raymond Hancock [c], Javier de la Villa [d], María Adoración Solórzano [e]

[a] *Faculty of Geological Sciences, Complutense University of Madrid, Spain*

[b] *Génie Géologique, France*

[c] *The University of Newcastle, Australia*

[d] *Spanish Network on Mine Rehabilitation, Spain*

[e] *Regional Government of Castile-La Mancha, Spain*

Abstract

At the 2022 Mine Closure Conference, we presented the ongoing geomorphic rehabilitation, landscape evolution modelling and geochemical stabilisation works for the LIFE RIBERMINE project at Peñalén (Spain) and Lousal (Portugal). Two years later, we describe the completion of the project at the Spanish location, focusing on finishing of the geomorphic regrading, by imprinting 'mature' catchments (using GeoFluv – Natural Regrade) at the former waste dumps and in 'sculpting' strikingly 'natural' limestone cliffs at a sector of the mine highwall (using the Talus Royal method). The total area subject to geomorphic regrading has been of 13.05 ha, from which 11.06 ha are fluvial geomorphic rehabilitation and 1.99 ha of hard rock geomorphic landforming. The total earth movement has approached 250,000 m^3. The complete and correct construction of the Talus Royal has been the main novelty from 2022 to 2024 and has been a clear success, since we were able to accurately build the design, demonstrating that it is a feasible technique to be included in mine closure plans.

The project monitoring has been broad and diverse. We focus on measuring soil erosion in the field with temporary check dams since sediment spill was the main environmental problem to solve at the Spanish site. From a pre-rehabilitation sediment yield of 353 t ha^{-1} yr^{-1}, we have measured, for the post-rehabilitation scenario:

- *external west waste rock dump (WRD) (7.4 t ha^{-1} yr^{-1})*
- *external east WRD (3.1 t ha^{-1} yr^{-1})*
- *in-pit backfilling (7 t ha^{-1} yr^{-1}).*

SIBERIA modelling at such sites predicted results very close to these values.

The effective results of LIFE RIBERMINE have allowed the transference of such geomorphic-based solutions to about 80 ha of new rehabilitation projects of abandoned mines in Spain, already completed. Two of them resulted from the recovery and use of bond guarantees by regional administrations, four projects funded by the European Union (EU) Recovery, Transformation and Resilience Plan (Next Generation EU funding), two sites for a mine company in Spain (SAMCA), and even one example in civil works. LIFE RIBERMINE has also been a training site for companies from Sweden (LKAB) and Colombia (Carbones del Cerrejón Limited, Glencore).

Keywords: *abandoned mines, geomorphic rehabilitation, soil erosion, landscape evolution models*

[*] Corresponding author.

1 Introduction

LIFE RIBERMINE is a European Union (EU) EUR 2.95 M funded project for solving fluvial pollution downstream of two sites of the Iberian Peninsula, Lousal in Portugal (Acid Drainage Mine) and Peñalén in Spain (river siltation) by using best available techniques in mine rehabilitation. These two cases represent very typical scenarios of abandoned mines, where the main environmental impact of mining is hydrologic (Mossa & James 2021).

In both cases, Lousal and Peñalén, the focus of the project has been implementing different geomorphic rehabilitation solutions, due to evidence showing they lay the foundation for erosion control, from the short to the long-term, once they are expertly combined with soil and vegetation restoration. An additional focus at Lousal was chemical remediation. A geomorphic approach to mine rehabilitation and closure is well described by Toy & Chuse (2005), Sawatsky et al. (2008) and Bugosh & Epp (2019), among others.

Martín Duque et al. (2022) made a first description of the LIFE RIBERMINE project. Hancock & Martín Duque (2022, 2024) have reported the SIBERIA modelling at the Spanish location. Sánchez Donoso et al. (2024) explain in detail the Portuguese scenario. Here, we focus on unfolding the completion of the project at the Spanish location, centring on the geomorphic landforming, soil erosion monitoring, and on the outstanding replications and transference of this project. These contents are this paper's objective.

The mine subject to rehabilitation, Santa Engracia, is located at the edge of the *Alto Tajo* natural park, at the Iberian mountain range, east-central Spain (Figure 1), within a Natura 2000 Network site and within the *Comarca de Molina-Alto Tajo* Geopark by UNESCO. A detailed description of the site is provided elsewhere (Martín-Moreno et al. 2018; Zapico et al. 2018).

Figure 1 Study area: location of the Santa Engracia mine, Peñalén municipality, within the Guadalajara province, Castile-La Mancha Region, Spain. The mine is located within the Iberian Mountain Range, at the head of the Tajo (Tagus) river basin, at the edge of the Alto Tajo Natural Park

2 Methods and results

LIFE RIBERMINE has displayed a whole set of methods for mine rehabilitation, specific for landforms, soil or vegetation, among others, combining them with a holistic approach. This paper will only describe those

dealing with landform design, with focus on the Talus Royal – since this is scarcely known in mine rehabilitation – and on soil erosion monitoring – since this is the key performance indicator at a higher significance within this project. We explain only the Spanish location since the Portuguese one has already been described by Martín Duque et al. (2022) and Sánchez Donoso et al. (2024).

2.1 Landform design and construction

Table 1 gathers the total areas subject to geomorphic landform design and later construction within LIFE RIBERMINE at the Santa Engracia mine, Spain. Figure 2 allows a visualisation of the earth movement involved, around 250,000 m^3 of cut, redistributed infill areas according to the designs. We are fully aware that these surfaces and volumes are really small for a global framework of large mines. However, they signify a typical mine rehabilitation project in Spain. In addition, they have demonstration value and it must be considered that they have been completed in a highly sensitive landscape (at the edge of a Natural Park) in a highly unstable setting (for water erosion and mass movements) from a physiographic point of view, located at the very rim of a plateau and canyonland-type landscape, with more than 400 m of relief, in highly erodible materials (sands) and under highly erosive conditions.

Table 1 Areas subject to geomorphic-based rehabilitation within LIFE RIBERMINE at the Santa Engracia mine (Peñalén, Guadalajara, Spain)

Method and location	Horizontal area (ha)	Slope area (ha)
GeoFluv – Natural Regrade	**10.41**	**11.06**
In-pit waste dump – backfilling	5.68	5.99
External west waste rock dump	1.70	1.82
External east waste rock dump	3.03	3.25
Talus Royal	**1.63**	**1.99**
Scree slope (transition to GeoFluv)	1.06	1.23
Hard-rock (cliffs)	0.57	0.76
Total	**12.04**	**13.05**

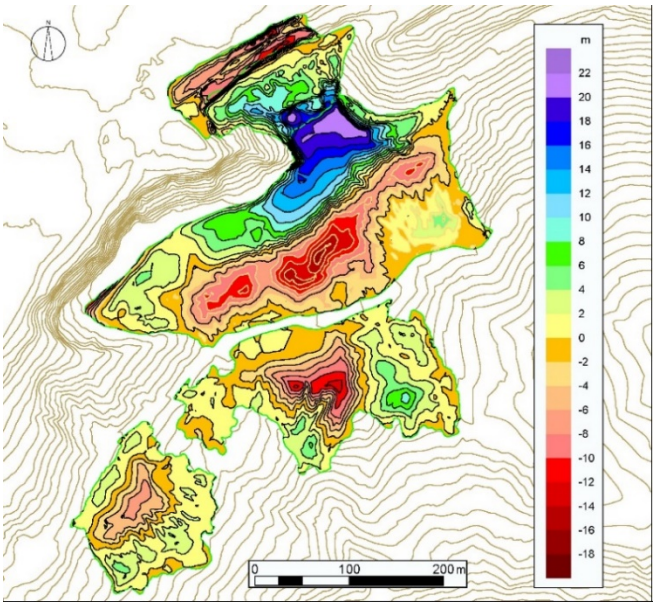
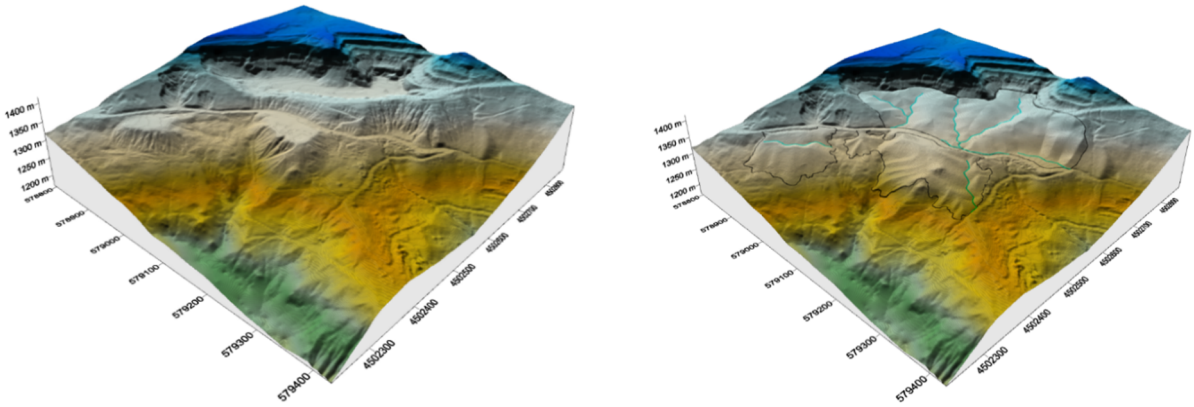


Figure 2 Cut depths and fill elevations involved at the Santa Engracia mine geomorphic rehabilitation

2.1.1 GeoFluv – Natural Regrade

The GeoFluv – Natural Regrade method has been extensively explained and referenced for mined land rehabilitation, and therefore, we suggest the reader to see details of it elsewhere. For example, Zapico et al. (2018), Bugosh & Epp (2019), or Martín Duque et al. (2022). Here, we only display the geomorphic landform design (Figure 3) and a visualisation of the final result of its construction (Figure 4).



(a) (b)

Figure 3 (a) Pre-restoration topography of the Santa Engracia mine; (b) Geomorphic landform rehabilitation design, through GeoFluv – Natural Regrade, showing: the boundaries of the designs (black line), the main designed fluvial channels (blue lines)

(a) (b)

(c)

Figure 4 (a) The Santa Engracia abandoned mine in March 2020 (photo by DIEDRO); (b) Once the first phase of the rehabilitation (external waste rock dumps) was finished (May 2021, photo by MA Langa); (c) End of the rehabilitation project (May 2024, photo by MA Langa). For May 2021 and 2024, notice the good fit between the design (Figure 3) and the final results of the landforming

The cut volume involved in the GeoFluv – Natural Regrade landform reshaping has been of 216,621 m^3 of cut, reallocated infill zones based on the computer-aided design, it is to say, with balanced earth work, plus 17,436 m^3 of carbonatic colluvium imported as growth medium.

The main difficulty of this project has been the need of building landforms designed with GeoFluv – Natural Regrade in very steep terrain. Table 2 and Figure 5 show the slope gradient result of the built landscape with unconsolidated waste materials. As it can be noticed, there is a high percentage of the reshaped land above 33% (1V:3H), which was difficult for equipment operations, but also the areas above 40% (1V:2.5H) and above 50% (1V:2H) are high. However, skilful machinery operators of excavators and bulldozers were able to build them.

Table 2 Slope report for the geomorphic rehabilitation of Santa Engracia mine

Slope range	Horizontal area (m^2)	Slope area (m^2)	% of total area
<20% (<1V:5H)	24,072.74	24,283.37	23.1
20–33% (1V.5H–1V:3H)	31,220.55	32,314.59	30.0
33–40% (1V:3H–1V:2.5H)	19,143.34	20,386.02	18.4
40–50% (1V:2.5H–1V:2H)	18,795.84	20,563.60	18.1
>50% (>1V:2H)	10,833.40	12,674.26	10.4
Total	104,065.87	110,221.83	100
Total (ha)	10.41	11.02	–

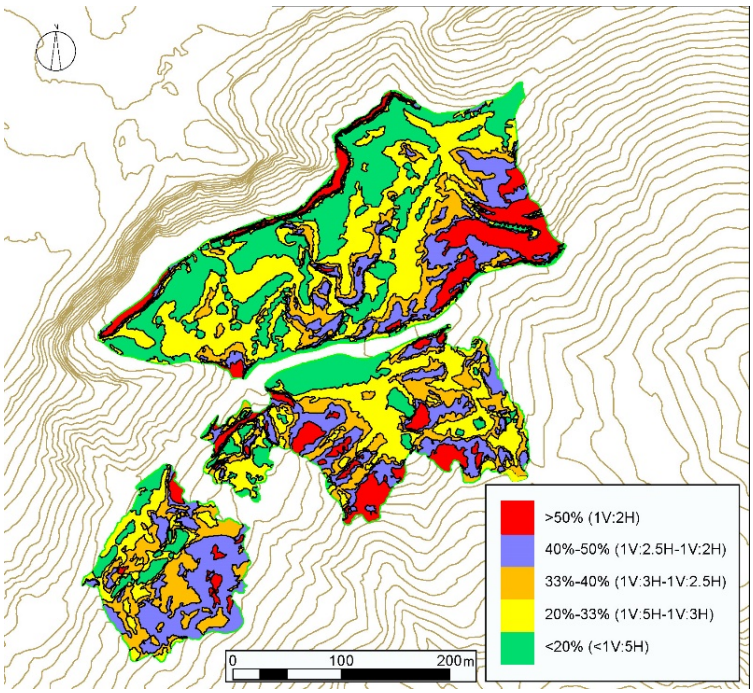


Figure 5 Gradient slope zones of the geomorphically regraded waste dumps at Santa Engracia Mine

This situation forced application of a specific soil and vegetation treatment at these very steep slopes, consisting of:

1. spreading first a mix of carbonatic colluvium and a mix of sheep and hen manure as topsoil
2. spreading seeds and mulch harvested in the local pastures over the soil
3. covering the mulch with a coconut organic net.

At some locations, with slopes above 50 %, using a large crane was required (Figure 6).

(a) (b)

Figure 6 Use of crane for the soil–vegetation treatment at the steepest slopes of LIFE RIBERMINE. (a) Aerial view; (b) Detail

At slopes below 40%, the soil–vegetation actions were:

1. spreading a mix of local carbonatic colluvium and sheep manure as topsoil
2. seeding native grass and shrub species
3. after the second year, once the soil was stable, planting trees characteristic of the Natural Park.

However, as a demonstrative project, beyond what it was, we have developed new techniques of mine restoration, such as:

1. using a decompacting implement, invented and patented by RIBERMINE personnel (previous to the project), for decompacting the soil
2. using a new procedure as a seed bank translocation method
3. stubble crops placement for reducing erosion and creating favourable conditions for vegetation development.

2.1.2 Talus Royal

The procedure by which hard rock excavations and earth movement in general remains to be based on standard criteria, with homogeneous topographic design gradients (such as 1V:2H, for example). As far as blasting is concerned, the almost universal technique for hard rock cuts at infrastructures (roadcut, platforms) is pre-cut blasting (blasting holes spaced from 0.5–1 m), trying to get the most perfect vertical or inclined rock planes. The main purpose of these practises is to guarantee precise geometry and pseudo stability. However, such conceptions overlap inevitably with heterogeneous geological settings, generating mass movement or surface instabilities. Once they occur, gunite, iron bolts and different types of meshes are used, to stabilise the rockfalls and slides caused by gravity. The visual and ecologic integration of such rock surfaces is also very weak. If gunite is used, the surface of the parent rock is totally 'sealed'. In mines and quarries pre-cutting is not generally used, because the security constraints are lower and because it has an additional cost. Therefore, mass shootings are directly applied against the cutting fronts, aiming to pulverise the rock and make it easily extractable with the result of leaving fractured rock fronts unsightly and evolving (unstable), as it happened in the case of the Peñalén mine.

As a more environmentally friendly and restorative solution, we used the Talus Royal method. The Talus Royal method is a geomorphic alternative to the common designing of building outslopes and highwalls in hard rock settings. It aims to replicate natural cliffs, at those artificial excavation scenarios, trying to maintain the character, complexity and harmony of natural bluffs. This method has been developed and registered by

the French geological engineer Paul Royal (Talus Royal 2024). In France, it is widely used in roadcuts. Somehow, it has a similar approach to one developed in the 1990s in the UK by the Limestone Research Group, of the Manchester Polytechnic (Gagen & Gunn 1988; Gunn et al. 1992; Gunn & Bailey 1993), following pioneering ideas in this field by Humphries (1977, 1979).

The Talus Royal designs involve a deep understanding of the local geology and how it has been eroded over the geomorphic history, identifying clearly, for example, which joints are those that drive the final escarpment landforms. Once the design is produced, specific rehabilitation blasting needs to be projected, which is different to the mine production, or pre-cut blasting. The aim is reshaping bulk material to landforms that are consistent with the local geomorphological setting. For that, the blasting parameters are modified, in order to expose the 'natural' architectural potential of the mine highwalls. Once the blasting occurs, excavators remove the loose rock blocks, leaving 3D rock faces, similar to natural ones. Finally, manual 'purges' are needed, in order to remove small loose rock blocks. Additional details of the Talus Royal design for LIFE RIBERMINE appear at Martín Duque et al. (2022). Figures 7 and 8 show different phases of the building process. Figures 9 and 10 show the final results.

(a)

(b)

(c)

Figure 7 (a) Excavator cleaning the limestone rock cliff of the former highwall of the Santa Engracia mine, after its 'rehabilitation' blasting; (b and c) Excavator, guided by Paul Royal, removing loose rock blocks, in order to get a 3D 'natural' rock face

Figure 8 Manual 'purges' on a reshaped Talus Royal limestone cliff at LIFE RIBERMINE

(a) (b)

Figure 9 (a) Starting point of the Santa Engracia mine highwall (photo by DIEDRO). The upper part is an alternation of limestone (beige) and marls (grey). The lower part (white and pink) are highly erodible kaolinitic sands; (b) Image after completion of the Talus Royal (photo by MA Langa). Notice how the highly erodible kaolinitic sands, highly stable under water erosion, have been covered by a limestone scree slope, avoiding such erosion

Figure 10 Detail of the upper section of the Talus Royal at the Santa Engracia mine (photo by MA Langa)

The cut volume involved in the Talus Royal landform reshaping has been of 32,500 m^3 of cut, redistributed infill areas according to the design.

2.2 Soil erosion monitoring

As we advanced, we put emphasis on the soil erosion monitoring, since this is the key performance indicator with a higher relevance for evaluating the success of LIFE RIBERMINE. On this, let us remember that the high sediment spill to the Tajo river system, reaching values as extraordinary as 353 t $ha^{-1} yr^{-1}$, was the main problem to solve.

To measure the post-restoration sediment yield, we followed a methodology used for similar purposes by Bugosh & Epp (2019) at La Plata mine (New Mexico, United States). Three temporary sandbag dams to contain the sediment discharge generated at different rainfall events, were constructed at each of the three locations of the Santa Engracia mine (Figure 11):

- in-pit waste dump (#1)
- external east waste rock dump (#2)
- and external west waste rock dump (#3).

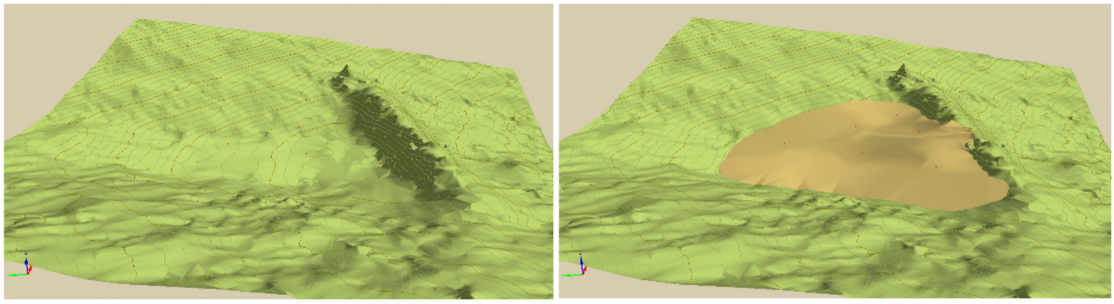
(a) (b)

Figure 11 Building process of the temporary dam #1. (a) Sand bags; (b) Once covered with a geotextile

At each bowl upstream of these dams we installed a series of sediment pins (steel bars) and surveyed them with a differential GPS Leica 1200. We then took repetitive measurements at the sediment pins matrix of each of the three temporary dams. The distance from the top of the pin to the ground surface measurement after a storm, or a group of storms, could be compared with the previous measurements, to determine the change in ground surface elevation at the pin (Figure 12). During the whole experiment, temporary dam #1

had to be cleaned several times, but not #2 and #3. The coordinate values, x, y, and z for each pin in the matrix, with the temporary dams empty and filled, were then used to generate a three-dimensional surface model using the Carlson Natural Regrade and Civil computer-aided design software. The surface models are triangular irregular network (TIN) models. The difference between repeated TINs from each of the three temporary dams were compared to study the changes in sediment over the periods corresponding to the TINs, obtaining volume of sediment for each dam (Figure 13). We then calculated the bulk density, by means of the ring method (Blake 1965), by using samples taken at the sediments retained at these check dams. The bulk density measured was 1.34 g cm^{-3}. Volume times bulk density yielded mass (t) for each dam, which once related to the area gave t ha^{-1}. Finally, relating this data with time, we obtained erosion rates in t ha^{-1} yr^{-1}. Table 3 shows the results.

Figure 12 View of the temporary sediment dam #1 after sedimentation, at the process of measuring the rod bars



(a) (b)

Figure 13 (a) Triangular irregular network (TIN) of the temporary check dam #1, clean of sediment; (b) TIN after sediment fill

Table 3 Summary of the erosion monitoring carried out at the geomorphically restored former waste dumps of the Santa Engracia mine (Peñalén, Guadalajara, Spain)

Check dam	Period of monitoring (months/years)	Watershed area (ha)	Sediment volume (m^3)	Sediment mass (t)	Measured erosion rates (t ha^{-1} a^{-1})	Erosion rates from SIBERIA (t ha^{-1} a^{-1})
# 1	20-01-2022/22-01-2024 24 months/2 years	1.14	11.94	15.99	6.97	15.2
# 2	11-05-2022/22-01-2024 20.5 months/1.7 years	0.27	2.57	3.44	7.40	6.3
# 3	11-05-2022/22-01-2024 20.5 months/1.7 years	0.74	2.92	3.91	3.12	5.2

3 Additional actions, replication and transference

RIBERMINE has catalysed securing EUR 1.7 M of additional funding for complementing the LIFE project objectives, such as:

- construction of new drainages and rip-rap ditch stabilisation, budget of 0.13 M EUR
- removal of a sediment check dam downstream of the restored mines, due to RIBERMINE success, budget of EUR 0.70 M (a and b actions funded by the Tagus Watershed Administration, *Confederación Hidrográfica del Tajo*)
- guaranteeing EUR 0.82 M of the Next Generation EU funding for restoring another mined site within the Municipality of Peñalén (Virgen de La Torre), completed in May 2024, and enlarging the Talus Royal operation.

The Next Generation EU funding projects are outstanding by their significance. On 21 June 2020, the European Union agreed, as a response to the economic and social crisis caused by COVID-19, to start the highest financial support program of its history, called Next Generation EU. The aim was fostering innovation and reforms for the Member States to achieve a sustainable and resilient recovery after the pandemic, promoting the ecologic and digital priorities of the EU. With such a complex program one investment branch was for 'Ecosystem restoration and green infrastructure', including a group of actions with the aim of recovering areas degraded by mining activities. Within that group, a few of them adopted the LIFE RIBERMINE geomorphic rehabilitation solutions.

As a synthesis, the effective results of LIFE RIBERMINE have allowed the replication of such geomorphic-based solutions to a total of around 80 ha of new geomorphic-based mine rehabilitation projects (but also some civil works) already completed. Table 4 gathers the details of such replicas. Figures 14 to 18 show comparisons of pre-rehabilitation and post-rehabilitation scenarios of some of those examples.

Table 4 Compilation of replication sites of LIFE RIBERMINE

#	Name (company)	Location	Country	Type of mine	Area (ha)
Recovery of bond guarantees by regional administrations					
1	Humanes de Mohernando	Guadalajara	Spain	Sand and gravel	0.6
2	Numancia de La Sagra	Toledo	Spain	Clay	8.5
Projects funded by the EU Recovery, Transformation and Resilience Plan (Next Generation)					
3	Virgen de La Torre	Guadalajara	Spain	Kaolin sands	7.2
4	Alpedrete	Madrid	Spain	Granite	6.3
5	San Quintín	Ciudad Real	Spain	Metallic (Pb, Zn)	37.5
6	Cabezo – La Lámpara	Valencia	Spain	Kaolin sands	4.1
Replication for mining companies					
7	San Luis (SAMCA)	Cuenca	Spain	Kaolin sands	9.5
8	M Pilar (SAMCA)	Cuenca	Spain	Kaolin sands	7.1
Replication at civil works					
9	Illescas – Montepino (Urban Construcción)	Toledo	Spain		2.5
Training to mining companies					
10	Svappavaara (LKAB)	Kiruna	Sweden	Iron	
11	Cerrejón (Glencore)	La Guajira	Colombia	Coal	

(a) (b)

Figure 14 (a) Virgen de La Torre abandoned mine before its geomorphic-based rehabilitation, replicating LIFE RIBERMINE techniques (June 2022); (b) After the geomorphic regrading and topsoiling (May 2024). Project led by the Castile-La Mancha regional government (both images by TRAGSA)

(a) (b)

Figure 15 (a) One of the San Quintín abandoned metallic mined sites (photo by P.G Zamorano, UCLM); (b) Geomorphic design. Project led by the Castile-La Mancha regional government, currently under construction

(a) (b)

Figure 16 (a) Abandoned granite quarry in Alpedrete (Madrid) (November 2023); (b) Geomorphic-based rehabilitation (April 2024). Project led by the Madrid regional government, *Comunidad de Madrid* (CAM) (photos by Hugo Torres and Jaime Fesser)

(a) (b)

Figure 17 (a) M. Pilar active mine (3D reconstruction as for July 2020); (b) Geomorphic-based rehabilitation (May 2024). The importance of this case is that it represents and active mine (photos by EUROARCE - Grupo SAMCA)

(a) (b)

Figure 18 Geomorphic rehabilitation of artificial terrains of civil works, at the Transportation City of Illescas–Montepino (Toledo, Spain). (a) Image before the intervention, July 2023; (b) Image after the geomorphic landforming, and revegetation, April 2024 (both images by Urban Construction)

A curious but notable outcome of LIFE RIBERMINE is that this project appears in the second version of the well-known book *101 Things to Do with a Hole in the Ground* (called *102 Things to Do with a Hole in the Ground,* Whitbread-Abrutat & Lowe 2024), being the only example, worldwide, of geomorphic mine rehabilitation within that book.

4 Discussion

The sediment yield monitoring has demonstrated that the physical pollution, siltation to the Tagus fluvial system from the abandoned Santa Engracia mine site of Peñalén (Spain), has been removed. The project allowed lowering the sediment spill from 353 t ha^{-1} yr^{-1}, measured by Martín-Moreno et al. (2018), to values ranging 3–7 t ha^{-1} yr^{-1}. SIBERIA modelling at such sites predicted results very close to these values, ranging between 5.2 and 15.2 t ha^{-1} yr^{-1}. Our interpretation of the difference is that the 15.2 t ha^{-1} yr^{-1} value was obtained at the in-pit location (which has higher slope gradients) completed in 2024, and the monitoring at this in-pit site has been carried out at the lowest gradient part.

The measured erosion rates here 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; FAO 1988) and much lower than what is considered a target erosion rate for rehabilitated mine sites by the Australian Queensland Department of Mines and Energy (Williams 2000). The values are similar to successful geomorphic-based mine rehabilitations in the vicinity,

where Zapico et al. (2018) measured 4.02 t ha^{-1} yr^{-1} (at nearby Machorro mine). The best evidence that the sediment spill to the Tajo river has been solved is that the Tagus Watershed Administration removed a large sediment check dam downstream of the Santa Engracia mine, built in 2010 to avoid sediment emissions.

Regarding the Talus Royal action, it is clear that it will have a great benefit in stabilising the highwall, since the highly erodible kaolinitic sands are covered with a limestone rocky scree slope. The shortcoming is that, due to budget limitations, it could not be applied to the whole highwall. The application of the Talus Royal at an abandoned mine was intended as more of a demonstration project, but it could be applied more effectively at active mines. Although the traditional mass blasting and operations could be used along most of the mine operations, for closure, the final hard rock surfaces could be designed following the Talus Royal method with the benefits of a stable design and having a much higher visual and ecologic value.

Although RIBERMINE and most of its replicas apply to abandoned mines, our solutions are better implemented in active mines, globally, from the beginning of the planning phases. In this sense, there is currently a good opportunity in Europe for geomorphic-based mine rehabilitation solutions, since there is a need for a revival of Europe's domestic mining in order to reduce the continent's dependence on minerals (as rare earths) from outside; a situation that has aggravated with the Ukrainian war. In this framework, the contribution of RIBERMINE for developing environmental restorative mining in Europe and elsewhere can be enormous.

5 Conclusion

LIFE RIBERMINE has been an Iberian geomorphic-based mine rehabilitation project. At the Spanish site (Santa Engracia abandoned mine), we have applied a geomorphic approach for the landform design of the two common settings of most mines: unconsolidated waste material and hard rock highwalls. Specifically, we used the GeoFluv – Natural Regrade method for the landform design of the former waste rock dumps and the Talus Royal method for the former highwall. As far as we know, this is the only project worldwide, which has combined those two geomorphic rehabilitation solutions for such different geologic settings, hard rock and 'soft' (unconsolidated) wastes. This circumstance makes this project a demonstrative one which can inspire other mine rehabilitation and closure solutions.

The main environmental problem of the Santa Engracia abandoned mine was a very high sediment spill to the Tajo fluvial system, within a Natural Park, with pre-rehabilitation erosion rates of 353 t ha^{-1} yr^{-1}. After having adopted the geomorphic-based rehabilitation, completed with soil and vegetation actions, we have removed such physical pollution. Two years of soil erosion monitoring generated erosion rates ranging 3–7 t ha^{-1} yr^{-1}. A former SIBERIA modelling forecasted soil erosion rates between 5.2 and 15.2 t ha^{-1} yr^{-1}. The adjustment between those two values is noticeable.

The Talus Royal implementation at LIFE RIBERMINE was a success, since we were able to accurately build the design; demonstrating that it is a feasible technique to be included at mine closure. The good performance of LIFE RIBERMINE has allowed the transference of such geomorphic-based solutions to different mine rehabilitation projects. Two of them corresponding to the recovery and use of bond guarantees by regional administrations, four projects funded by the EU Recovery, Transformation and Resilience Plan (Next Generation EU funding), two sites of a mine company in Spain (SAMCA) and even one example in civil works. LIFE RIBERMINE has also been a training site for a Swedish company (LKAB) and a Colombian one (Carbones del Cerrejón Limited, Glencore), demonstrating that this facility has a value beyond the national scale.

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References

Blake GR 1965, 'Bulk density', in CA Black, DD Evans, LE Ensminger, JL White & FE Clark (eds), *Methods of Soil* Analysis. *Part 1. Physical and Mineralogical Properties*, American Society of Agronomy, Madison, pp. 374–390.

Bugosh, N & Epp, E 2019, 'Evaluating sediment production from native and fluvial geomorphic reclamation watersheds at La Plata Mine', *Catena*, vol. 174, pp. 383–398.

FAO 1988, *Sistemas de Labranza para la Conservación del suelo y del agua* (Tillage systems for soil and water conservation), Roma.

Gagen, P J & Gunn, J 1988, 'A geomorphological approach to limestone quarry restoration', in JM Hooke (ed.), *Geomorphology in Environmental Planning*, John Wiley & Sons, New York, pp. 121–142.

Gunn, J & Bailey, D 1993, 'Limestone quarrying and quarry reclamation in Britain', *Environmental Geology*, vol. 21, pp. 167–172.

Gunn, J, Bailey, D & Gagen, P 1992, *Landform Replication as a Technique for the Reclamation of Limestone Quarries*, HMSO, London.

Hancock, G & Martín Duque, JF 2022, 'Assessing the stability of a geomorphically reconstructed post-mining landscape: a case study of the Santa Engracia, Spain', in M Tibbett, AB Fourie & G Boggs (eds), *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 127–143.

Hancock, G & Martín Duque, JF 2024, 'Designing, building and assessing a geomorphically reconstructed post-mining landscape: a case study of the Santa Engracia mine, Spain', *Earth Surface Processes and Landforms (ESP-23-0398),* accepted for publication.

Humphries, RN 1977, 'A new method for landscaping quarry faces', *Rock Products*, vol. 80, no. 5, pp. 122H–122J.

Humphries, RN 1979, 'Landscaping hard rock quarry faces', *Landscape Design*, vol. 127, pp. 34–37.

Martín Duque, JF, Tejedor Palomino, M, Hancock, G, Martín Moreno, C, Sánchez Donoso, R & de la Villa Albares, J 2022, 'Geomorphic landform design, landscape evolution modelling and geochemical stabilisation for mine closure at the LIFE RIBERMINE project, Spain and Portugal', in M Tibbett, AB Fourie & G Boggs (eds), *Mine Closure 2022: Proceedings of the 15th International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 65–78, https://doi.org/10.36487/ACG_repo/2215_01

Martín-Moreno, C, Martín Duque, JF, Nicolau, JM, Muñoz, A & Zapico, I 2018, 'Waste dump erosional landform stability – a critical issue for mountain mining', *Earth Surface Processes and Landforms*, vol. 43, pp. 1431–1450.

Mossa, J & James, LA 2021, 'Geomorphic perspectives on mining landscapes, hazards, and sustainability', *Treatise on Geomorphology*, Elsevier, Berlin, pp. 1–37.

Sánchez Donoso, R, Martins, M, Tejedor, M, Esbrí, JM, Lillo, FJ, Pereira, AM, Martín Duque, JF 2024, 'Geomorphic-based mine rehabilitation coupled with AMD chemical stabilization in sulphide-rich ore deposits and soils: Insights from a pioneering intervention at the Lousal mine, Iberian Pyrite Belt', *International Journal of Mining, Reclamation and Environment*, vol. 38, no. 1, pp. 79–97, https://doi.org/10.1080/17480930.2023.2247698

Sawatsky, LF, Beersing, A & Ade, F 2008, 'Configuration of mine closure landforms — geomorphic approach', in AB Fourie, M Tibbett, IM Weiersbye & PJ Weiersbye (eds), *Mine Closure 2008: Proceedings of the Third International Seminar on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 35–45, https://doi.org/10.36487/ACG_repo/852_5

Schmidt, BL, Allmaras, RR, Mannering, JV & Papendick, RI 1982, *Determinants of Soil Loss Tolerance*, American Society of Agronomy-Soil Science Society of America, Madison.

Talus Royal 2024, *Talus ROYAL® Partout en France et en Europe* (Talus ROYAL® throughout France and Europe), https://www.2g.fr/talus-royal

Toy, TJ & Chuse, WR 2005, 'Topographic reconstruction: a geomorphic approach', *Ecological Engineering*, vol. 24, pp. 29–35.

Whitbread-Abrutat, PH & Lowe, R 2024, *102 Things to Do with a Hole in the Ground*, Eden Project.

Williams, D 2000, 'Assessment of embankment parameters', in WA Hustrulid, MK McCarter & DJA Van Zyl (eds), *Slope Stability in Surface Mining*, SME - Society for Mining, Metallurgy and Exploration, Littleton, pp. 275–284.

Zapico, I, Martín Duque, JF, Bugosh, N, Laronne, JB, Ortega, A, Molina, A, Sánchez, L 2018, 'Geomorphic reclamation for reestablishment of landform stability at a watershed scale in mined sites: the Alto Tajo Natural Park, Spain', *Ecological Engineering*, vol. 111, pp. 100–116.