Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds)

doi:10.36487/ACG_repo/2215_01

Geomorphic landform design, landscape evolution modelling and geochemical stabilisation for mine closure at the LIFE RIBERMINE project, Spain and Portugal

JF Martín Duque *Universidad Complutense de Madrid, Spain*

M Tejedor Palomino *Universidad Complutense de Madrid, Spain*

G Hancock *The University of Newcastle, Australia*

C Martín Moreno *Universidad Complutense de Madrid, Spain*

R Sánchez Donoso *Universidad Complutense de Madrid, Spain*

J de la Villa Albares *Regional Government of Castile-La Mancha, Spain*

Abstract

The environmental impact of mining on landscape systems is well recognised. New technologies for landscape reconstruction have been developed and advanced in recent decades alongside the recognition of the environmental impact and resultant societal expectation of a restored and integrated post-mining system. A post-mining landscape requires physical stability (and, if present, chemical stability). Australia, the United States, Canada, Chile and the European Union, among others, have mine regulations requiring non-polluting post-mining landforms. We describe mine closure actions in Spain and Portugal (LIFE RIBERMINE project) that integrate two geomorphic landform design techniques: (a) GeoFluv–Natural Regrade, for unconsolidated sandy waste dumps in Spain and pyrite waste deposits in Portugal, and (b) Talus Royal, for hard-rock residual highwalls in Spain. SIBERIA landscape evolution modelling has been used to evaluate the erosional stability of post-mining geomorphic landform designs in Spain. Acid mine drainage (AMD) chemical stabilisation and remediation measures were combined with geomorphic landform designs in Portugal. Design procedures of LIFE RIBERMINE took place in the years 2019 and 2020, being constructed in 2020, 2021 and 2022. Design and construction phases were executed as planned, with minor deviations. The monitoring procedures (lasting until 2029) are intended to verify the real effectiveness of such solutions. The improvement of the water quality downstream in the demonstration site of Spain (Santa Engracia mine, Peñalén) will be quantified by measuring the sediment emission-immission to water bodies. Erosion rate (sediment yield) at the Santa Engracia mine previous to LIFE RIBERMINE was 353 t ha^{-1} yr^{-1}. The target values after restoration should range between 4 and 15 t ha^{-1} yr^{-1}, forecasted by the SIBERIA modelling and measured by monitoring similar geomorphic-based solutions at nearby mines. Regarding turbidity, suspended sediment concentrations (SSC) at a pre-rehabilitation phase were 391 g l^{-1} and target values (baseline) are 24 g l^{-1}. In Portugal (Lousal, Grândola), where AMD is the main problem, it is expected that the dissolved potentially toxic elements' maximum concentration values of Pb (0.9 mg/L), Cd (0.5 mg/L), Zn (80 mg/L) and Cu (20 mg/L) are reduced to values at least closer to the values established by the Portuguese legislation for minimum water quality in surface waters (Pb – 0.05 mg/L, Cd – 0.01 mg/L, Zn – 0.5 mg/L, Cu – 0.1 mg/L). If the AMD treatment measures are effective, initial physicochemical values of pH (between 1.8 and 3.1) and conductivity (2.71–3.9 mS/cm) should also change to near common non-polluted water values (around pH – 7, conductivity – 0.75 mS/cm). LIFE RIBERMINE aims to significantly reduce mined land environmental contamination and to demonstrate the efficiency of a combination of some best available techniques for mine closure. The performance results can be used to consider applying the innovative rehabilitation and remediation designs to other mine locations, abandoned or active, elsewhere. These project remedies are expected to reduce post-closure expense and liabilities.

Keywords: *GeoFluv–Natural Regrade, Talus Royal, acid mine drainage, SIBERIA, LIFE Programme, European Union*

1 Introduction

1.1 Physical and chemical stabilisation in mine rehabilitation

Mining regulations in developed countries focus on guaranteeing, as a first step, physical and chemical stability of mine wastes and sites. Once this is assured, more ambitious goals, such as restoring ecosystem goods and services (ecological restoration), can be achieved. In Australia, there are clear requirements and guidelines to construct post-mining landforms that are safe, stable and non-polluting for humans, flora and fauna, and capable of sustaining land use after mining finishes. Howard et al. (2011) make a synthesis for different Australian states, referring to laws for Western Australia and Queensland and guidelines in such a direction in New South Wales. In Canada, mining legislation requests the reconstruction of 'self-sustained' landforms and ecosystems that are compatible with a healthy environment and the maintenance of other human activities. Until self-sustaining vegetation cover is established, Canadian legislation specifies the need for erosion control methods (Minister of Public Works and Government Services of Canada 1996). In the United States, regulations put emphasis on ensuring that reclaimed surfaces are stable against erosion, aiming to minimise offsite effects and avoiding potential changes in the hydrological balance, which generally occur through the release of runoff and sediment (NMMMD 2010). In Chile, the law regulating the closure of mine operations and facilities requires guaranteeing the physical and chemical stability of all sites where mining activities have taken place (Ministerio de Minería 2011). In Europe, the main law, as far as these physical-chemical issues are concerned, in mine rehabilitation is the mining waste directive 2006/21/EC (European Council 2006). This directive was subsequently transposed to the European Union (EU) state members. Spain, through the RD 975/2009 (BOE 2009), requires guaranteeing the stability of mining waste, and preventing soil, surface and groundwater pollution. Portugal sets standards by means of the *Decreto-Lei* 10/2010 (Diário da República 2010). Spanish RD 975/2009 and Portuguese *Decreto-Lei* 10/2010 are very similar, since they both are a transposition of 2006/21/EC. Also in Portugal, the issue of chemical stabilisation is regulated by the Portuguese *Decreto-Lei Nº 236/98* (Diário da República 1998). Finally, although they are not legal requirements, the World Bank and its International Finance Corporation (IFC 2007) have also specific technical physical and chemical stabilisation requirements of Good International Industry Practice, which are internationally applied in developing countries where domestic standards are less strict.

1.2 The LIFE RIBERMINE project

Within the legal framework just referred, we describe here the use of best available techniques for physical and chemical stabilisation of mine sites at the Iberian Peninsula (Spain and Portugal; Figure 1a), as part of the EU LIFE RIBERMINE project (https://liferibermine.com/en/homepage_en/). The LIFE (*L'Instrument Financier pour l'Environnement*) program is the EU's most important funding instrument addressing environment and climate actions. Physical stabilisation solutions are based on geomorphic design and erosion modelling, which in Portugal are combined with chemical remediation measures. The aim is the recovery of water quality downstream of the mined sites with an emphasis on transferable solutions.

In Spain, the post-mine landscape reconstruction focuses on abandoned kaolin mined sites in Peñalén (Guadalajara Province, Castile La Mancha Autonomous Community). Specifically, the ancient Santa Engracia mine (Figure 1c–g) created extremely poor water quality downstream due to suspended sediments (Figure 1h). The scenario previous to the LIFE RIBERMINE intervention showed an evolution from conventional (terraced) rehabilitation (Figure 1d) to a heavily gullied hillslope (badland) with an erosion rate of 353 t ha^{-1} yr^{-1} (Martín-Moreno et al. 2018) (see Figure 1d–g). The sediment yield from these highly eroded waste dumps was hydrologically connected with the Tajo River within a Natural Park, resulting in extremely poor water quality (Figure 1h). This is considered the most significant environmental problem of the Alto Tajo Natural Park. In 1990, an initiative with a budget of close to EUR 1 M using check dams downstream of the mines was ineffective at controlling the sediment load from the mine site (Martín-Moreno et al. 2018). Therefore, the goal of the LIFE RIBERMINE project was to remove the source of the sediment entering the Tajo fluvial ecosystems by ecological, geomorphic-based restoration of the Santa Engracia mine.

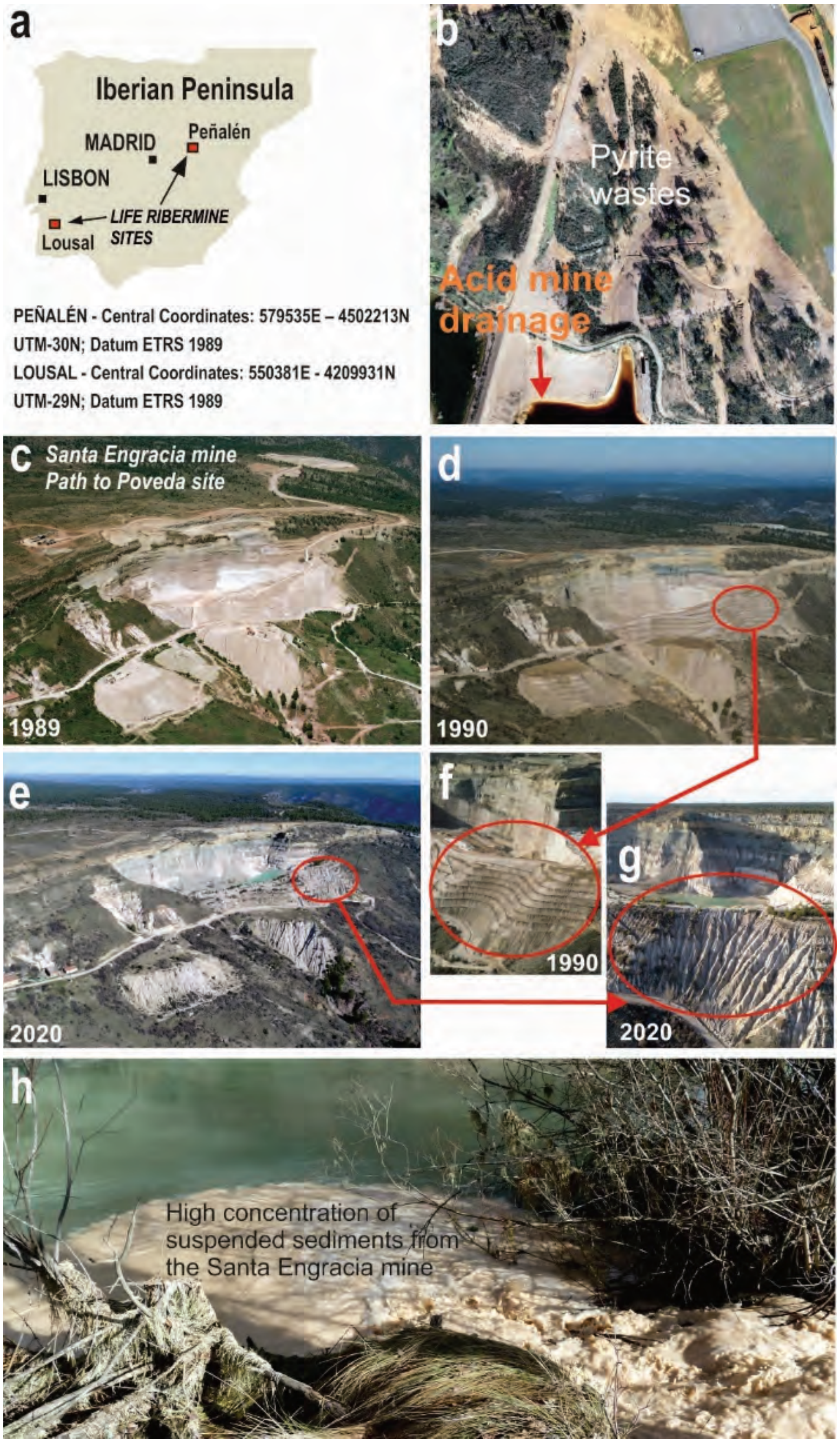

Figure 1 (a) Study area – location of the LIFE RIBERMINE sites in the Iberian Peninsula; (b) Intervention site at Lousal (Portugal), showing acid mine drainage downstream of pyrite wastes; (c to g) Santa Engracia mine (Spain); (c) Oblique aerial view of 1989 – a sidehill waste dump building process, close to completion; (d) Same site in 1990, rehabilitated with terraces (images by Paisajes Españoles); (e) Same site in 2020, showing 30 years of erosional evolution (image by DIEDRO). (f and g) Detailed comparison showing the severe gullying-badland erosion from 1990 to 2020. 1990, image by Paisajes Españoles. 2020, image by DGDRONE; (h) Solid suspended sediments entering the fluvial network downstream of the Santa Engracia mine

In Portugal, the degraded and polluted area subject to recovery was the Lousal mine, located in the Grândola municipality (Alentejo region). It was exploited between 1900 and 1988, primarily for pyrite, through surface and underground works (Luís et al. 2011). The mining legacy resulted in different types of mine wastes, ranging from varieties of waste rock deposits to tailings (Ferreira da Silva et al. 2009). A heavily polluted area due to tailing and waste material impoundment of fine-grained pyrite (Ferreira da Silva et al. 2009) was the area prioritised for remediation (Figure 1b). After the 1988 mine closure, environmental degradation of mine wastes and tailings prompted a rehabilitation program (RELOUSAL; Rehabilitation and Integral Development of the Lousal Mine) by the mining company (SAEPEC) and the Grândola town council. As part of this program, an acid mine drainage (AMD) passive treatment facility was implemented within the mining complex, next to the pyrite deposits. A system of artificial wetlands was constructed to reduce potentially toxic elements (PTE) content and to increase the pH of surficial waters draining into the Corona River (Oliveira et al. 2013). Upstream of the artificial wetlands, open limestone downdrains were constructed. The lack of a proper holistic treatment of the whole pyrite deposit led to accelerated erosion through rilling within the pyrite deposit, so the limestone blocks of the open limestone downdrains were covered with iron oxides. The failure was a combination of a lack of not comprehensively considering the whole pyrite deposit, but also not considering the occurrence of iron armouring of the open limestone downdrains without suitable subsequent maintenance works planned and budgeted. Therefore, LIFE RIBERMINE prioritised acting again in this most problematic head of the catchment area, intending to neutralise it, somehow, and therefore reducing the levels of AMD yielded to the artificial wetland system, main RELOUSAL action.

2 Methodology

Within LIFE RIBERMINE, a combination of different techniques of geomorphic landform design (GLD), landscape evolution modelling (LEM) and chemical stabilisation, for mine rehabilitation, has been used. In Peñalén (Spain), GeoFluv–Natural Regrade has been the GLD tool, and SIBERIA (LEM) was selected for evaluating the erosive performance of the designs. In Lousal (Portugal), GeoFluv–Natural Regrade was also used for GLD, combined with chemical remediation techniques. Each site intervention was also subject to soil recovery and revegetation, but we describe here only those actions focusing on GLD, LEM and chemical stability.

The GeoFluv–Natural Regrade designs had the main aim of projecting functional drainage networks connecting with the natural ones existing before both Iberian mines transformed the land. Figure 2 shows the pre-mining drainage network at Peñalén. GeoFluv is a GLD method that seeks to replicate landscapes similar to those that would naturally form by fluvial and hillslope processes under the climatic and physiographic conditions at the site. Suitable and stable reference areas need to be identified to provide design input values. The analogue and input design values for Peñalén are described at Zapico et al. (2018), being used in the area since 2017. The analogue and input design values for Lousal were gathered from the rolling uplands landscapes located near the hamlet of Faleiros, close to Lousal (unpublished). Natural Regrade is the software that aids users to make and evaluate GeoFluv designs in a computer aided design format from the input values. The GeoFluv method allows designing landforms and landscapes to function as mature 'natural' ones at the completion of restoration grading, topsoiling and revegetation. The method essentially compresses time, creating steady-state landscapes with approximate balances among erosive forces and resistances. The GeoFluv method and related examples have been described elsewhere (Bugosh & Epp 2019; Martín Duque et al. 2020, 2021; Zapico et al. 2018).

SIBERIA is a LEM that has been extensively used for erosion on post-mining landscapes by the Australian mining industry since the 1990s (Willgoose & Riley 1998; Hancock et al. 2008; Hancock & Willgoose 2018). SIBERIA provides visualisation of where erosion occurs and its type (i.e. gullies, rills), and offers erosion rates – both in t ha^{-1} yr^{-1} and denudation (mm yr^{-1}; it is to say, landscape lowering). The model can be run for decadal time scales but can also be run up to millennia. A summary of mine site application can be found in Hancock & Willgoose (2018).

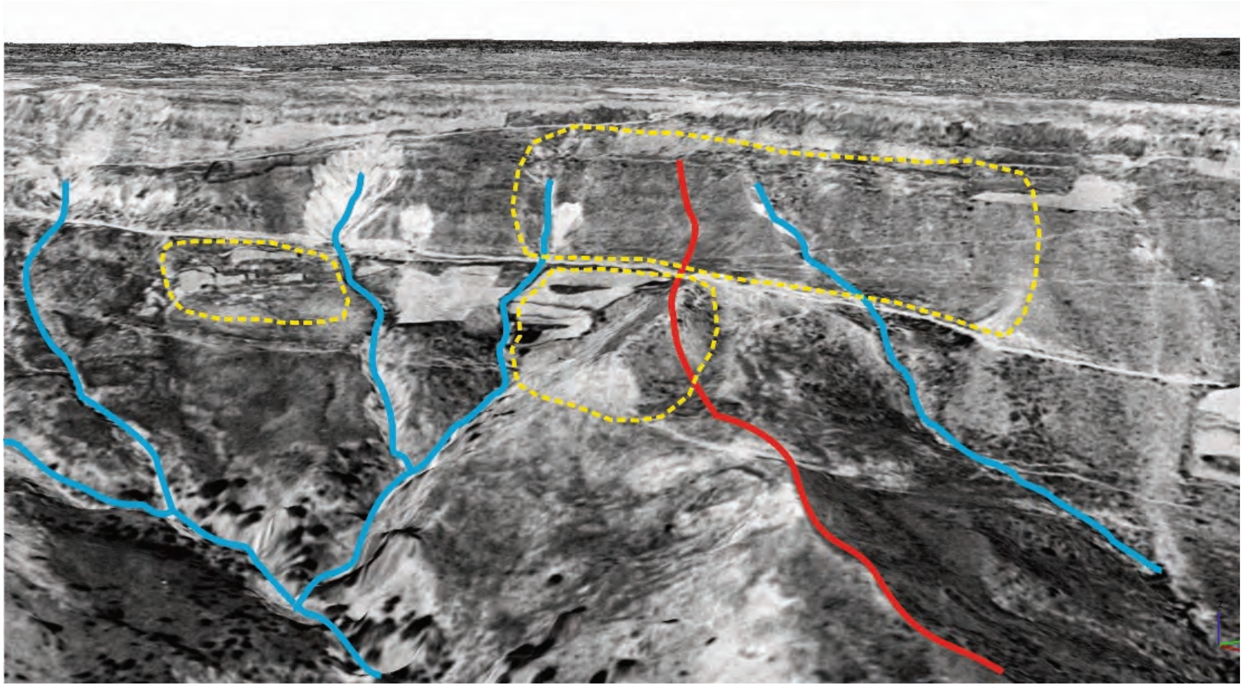

Figure 2 3D view of the Santa Engracia mine area in 1956, before the excavation and waste dumping transformation. Yellow dotted lines, areas transformed by mining. The small polygons are the waste rock dumps and the large polygon is the pit and in-pit waste rock dump. Blue lines, drainage network. Red line, divide, before the mine. From 1980 to 1990, both elements were obliterated by the mining activity. Finally, they are being restored within the geomorphic landform design of LIFE RIBERMINE (see Figure 3). Reconstruction from aerial photo restitution by JA Mezo Ortiz and I Zapico

Different techniques for replicating natural landforms in quarry highwalls and roadcuts have developed and been applied in Europe since 1977 (Gunn et al. 1992; Humphries 1977, 1979; Legwaila et al. 2015; or the Talus Royal https://www.2g.fr/talus-royal). In LIFE RIBERMINE, Talus Royal has been the method used for designing landforms at the residual hard-rock (limestone) highwalls of the mine that replicate the natural ones of the Alto Tajo canyon walls and cliffs. Talus Royal is a method of natural landform reconstruction invented by the French geologist engineer Paul Royal. It aims to provide maximum stability to hard-rock human excavations (such as road cuts or mining highwalls), avoiding severe ecological and visual impacts. The principle of the method is, first of all, to replicate the natural hillslopes or valley wall profiles. Then, at a detailed scale, to use the pre-cutting of the rock so as to release it according to pre-existing joints, fractures or stratification beds. Once these faces are exposed, they are already impregnated with oxide deposits, thanks to the water circulations through such fissures. This pre-patina will quickly recover in the open air an aspect comparable to the patina of the rock in the immediate environment. On the other hand, by using the natural pre-cutting of the rock, the slope 'released landforms' will be similar to those formed by natural erosion, which would inevitably use these fractures to progress. The small depressions obtained within the slope will constitute traps for fines, allowing a spontaneous recovery of vegetation. This natural process will be supported by the water supply from the pre-existing networks of joints forming these ecologic niches (see Talus Royal website: https://www.2g.fr/talus-royal).

As far as the chemical stabilisation measures are concerned, a soil cover was designed to be spread over the new 'natural' designed landforms at Lousal (Portugal). The cover is composed of two soil horizons with specific purposes: to help neutralise lateral subsurface water flows towards the drainage network and to provide a good foundation for plant growth (Figure 6). The surficial horizon (A, 10 cm of thickness) is composed of poultry manure and topsoil, while the lower horizon (B, 15 cm of thickness) is made of a mixture of clays and limestone gravel. This B-horizon should help neutralise the lateral subsurface flows, part of which would circulate through this soil amendment, that end up being return flows at the fluvial channels. Enhanced infiltration and subsurface water circulation through this horizon should prevent water stagnation and partially protect the pyrite wastes from chemical reactions. The open limestone meandering channels draping the reconstructed fluvial network would increase the geochemical stabilisation process. A complete earth movement and neutralisation of the pyrite deposit was not economically feasible. Therefore, the option of combining a geomorphic regrading with neutralising soil covers and open limestone meandering channels adapted to the new 'natural' catchment topography, thus managing the subsurface and surficial flows, was thought to be the most efficient solution. We recognise, however, that these actions will not totally solve the problem. This was not the main aim, but there was a need to help reduce AMD levels at the head of the Corona watershed, yielded to the artificial wetland system built by RELOUSAL. It was also recognised that the open limestone meandering channels for amelioration of AMD are effective for only a limited time, before the limestone lining becomes clogged with iron precipitates, which renders them ineffective. Therefore, regular replacement with fresh limestone blocks will be necessary, to preserve their functionality.

3 Results

Figure 3 shows the GeoFluv–Natural Regrade designs of the LIFE RIBERMINE project. Key morphological features of the design at Peñalén (Spain) are 110 m ha^{-1} of drainage density, 16.6 m for 'A' channel reaches and 37 m of maximum distance from ridgeline to channel's head (described in Zapico et al. 2018). The same features for Lousal (Portugal) are 30 m ha^{-1} of drainage density, 12 m for 'A' channel reaches and 10 m of maximum distance from ridgeline to channel's head. Figure 4 provides the proposed geomorphic design following the Talus Royal method (Peñalén) for replicating natural landform characteristics of the valley walls and cliffs of the Alto Tajo Natural Park. Figure 5 offers an example of the resulting digital elevation models after simulating erosion for 10 and 100 years at the west external waste dump of Peñalén (visible at the upper right; Figure 9). The erosion values associated with such modelling are 5.25 and 6.3 t ha^{-1} yr^{-1}, respectively (Hancock 2021). Figure 6 shows schemes of chemical stabilisation measures at Lousal, adapted to the GLDs.

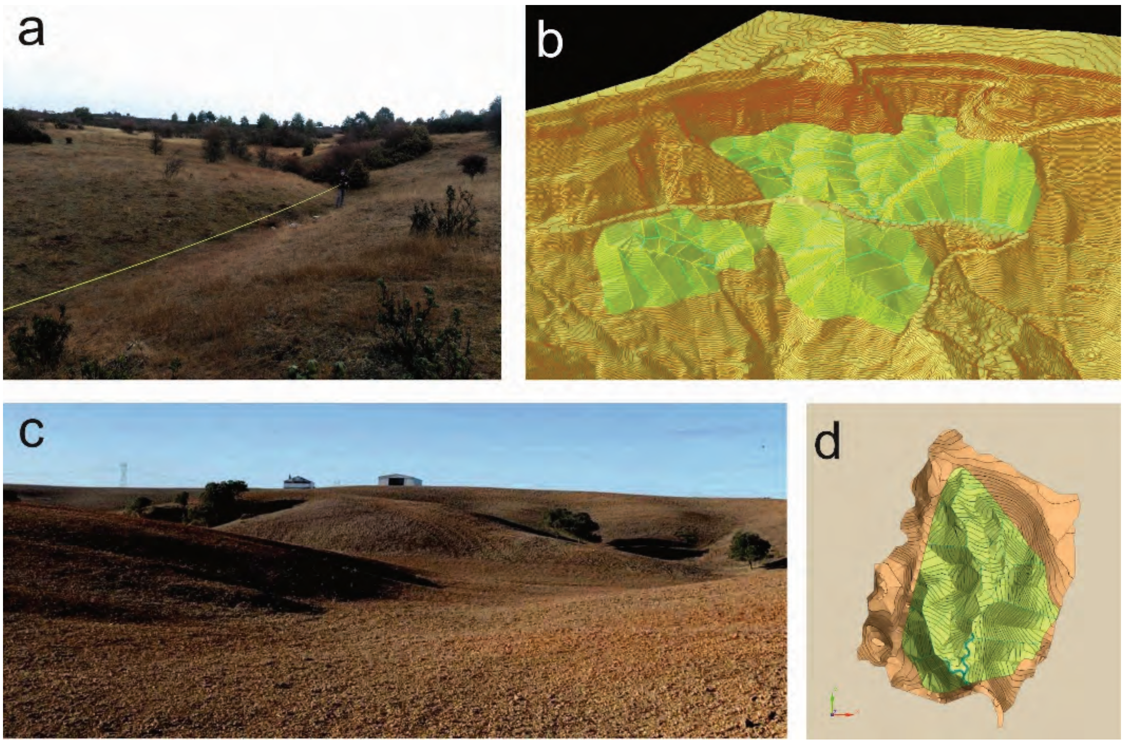

Figure 3 (a) Reference area; (b) GeoFluv–Natural Regrade landform designs for Peñalén (Spain); (c) Reference area (photo by Alvaro Pinto); (d) GeoFluv–Natural Regrade landform designs for Lousal (Portugal)

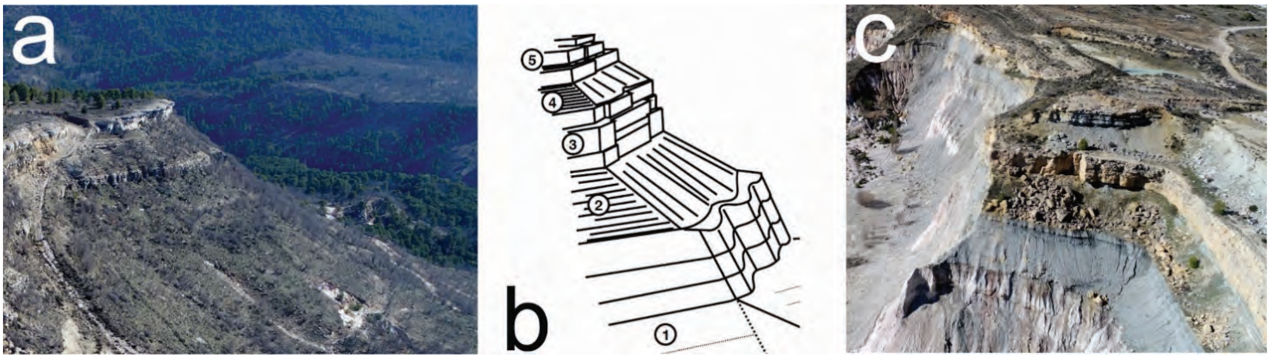

Figure 4 **(a) Typical hillslope profile of the surroundings of the Santa Engracia mine (Spain) at the Alto Tajo Natural Park; the limestone strata form ledges with vertical shape, whereas the marls and silica sand layers are shaped in a talus topography; (b) Proposed geomorphic landform design following the Talus Royal method, replicating the natural landforms of figure (a): (1) silica sand; (2) and (4) marls; (3) and (5) limestone; (c) Homogeneous-vertical pre-restoration profile of the upper part of the residual highwall of Santa Engracia mine, to be re-shaped as (a) following the (b) design. (a) and (c) images by DIEDRO**

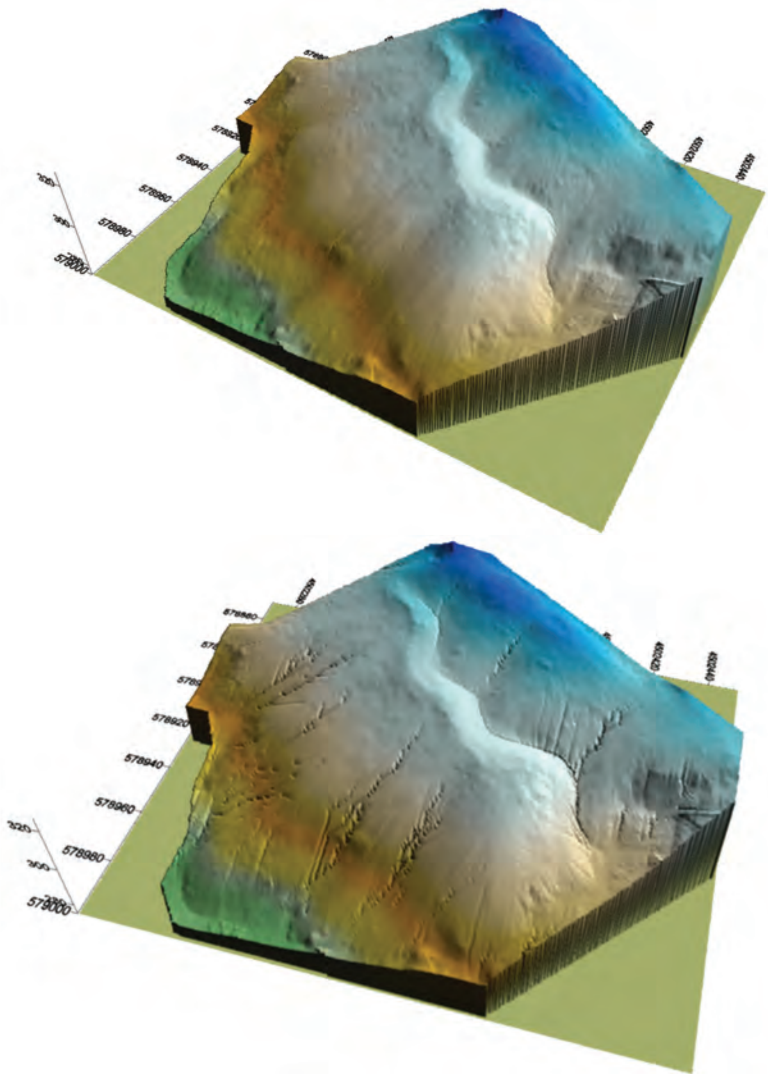

Figure 5 **Digital elevation model outcomes of the erosion modelling with SIBERIA of the external (west) waste rock dump at Peñalén (Spain) at 10 (top) and 100 years (bottom)**

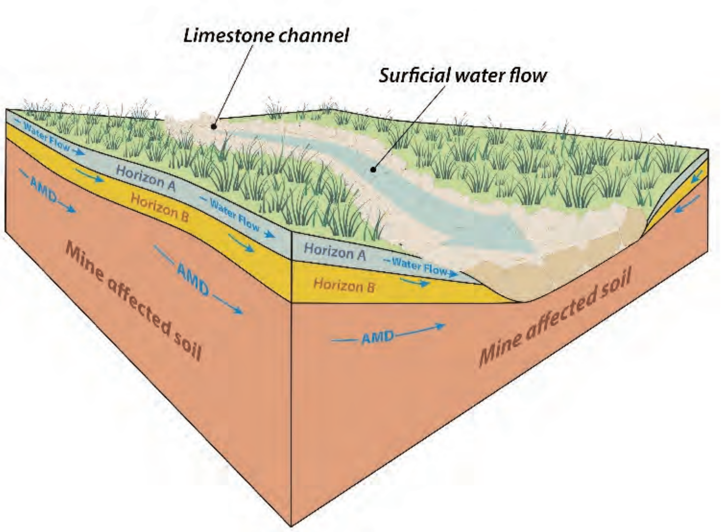

Figure 6 **Chemical stabilisation measures at Lousal (Portugal). Notice how the soil cover amendment and the open limestone meandering channels are adapted to a 'natural' landform design, addressing only lateral subsurface, return and surficial flows. The limestone drapes both bankfull and flood prone channel sections. Figure redrawn by Javier Lillo, after a schematic diagram by Cristina Martín (Sánchez-Donoso et al. 2021)**

4 Implementation

Figure 7 is a compilation of images of the construction phases, both at Peñalén (Spain) and Lousal (Portugal).

Figure 7 **Images of the construction phases: (a) Bulldozer and excavator sculpting a valley in Peñalén (Spain); (b) Bulldozer spreading topsoil (carbonatic colluvium) and regrading a zig-zag valley in Peñalén; (c) Meandering channel staked out for building in Lousal (Portugal); (d) Backhoe excavator spreading limestone gravel (soil cover) at Lousal; (e) Building process of an open limestone meandering channel at Lousal**

Figure 8 shows the blasting process at the top of the Santa Engracia (Peñalén, Spain) highwall. Figures 9 and 10 show comparisons of the pre- and post-rehabilitation scenarios at this same site. In Figure 9, the un-rehabilitated interior of the pit, which will be rehabilitated in the autumn of 2022, is clearly seen. Figure 10e shows how the rehabilitated site displays a good vegetation cover, with minimal erosion, after 1.5 years after intervention. Figure 11 shows the evolution of the intervention area in Lousal (Portugal).

Figure 8 Blasting process at the higher positions of the Santa Engracia (Peñalén, Spain) residual highwall; first phase for replicating natural cliffs following the Talus Royal method (image by Miguel Ángel Langa)

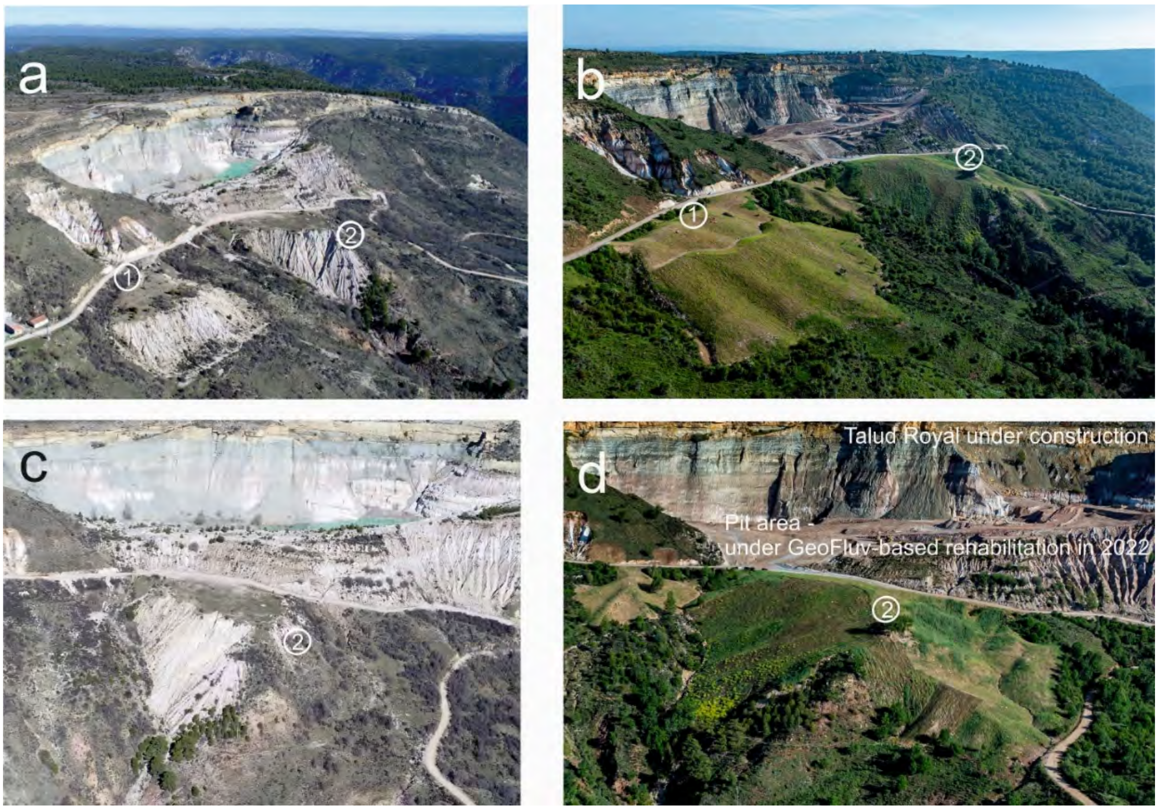

Figure 9 (a and c) Two different views of the pre-rehabilitated external waste rock dumps and pit of Santa Engracia mine (Peñalén, Spain), in March 2020 (photos by DIEDRO); (b and d) Aerial views of the same positions of (a) and (c), respectively, after geomorphic-based rehabilitation, in May 2021 (photos by MA Langa). Numbers show the same positions in different images

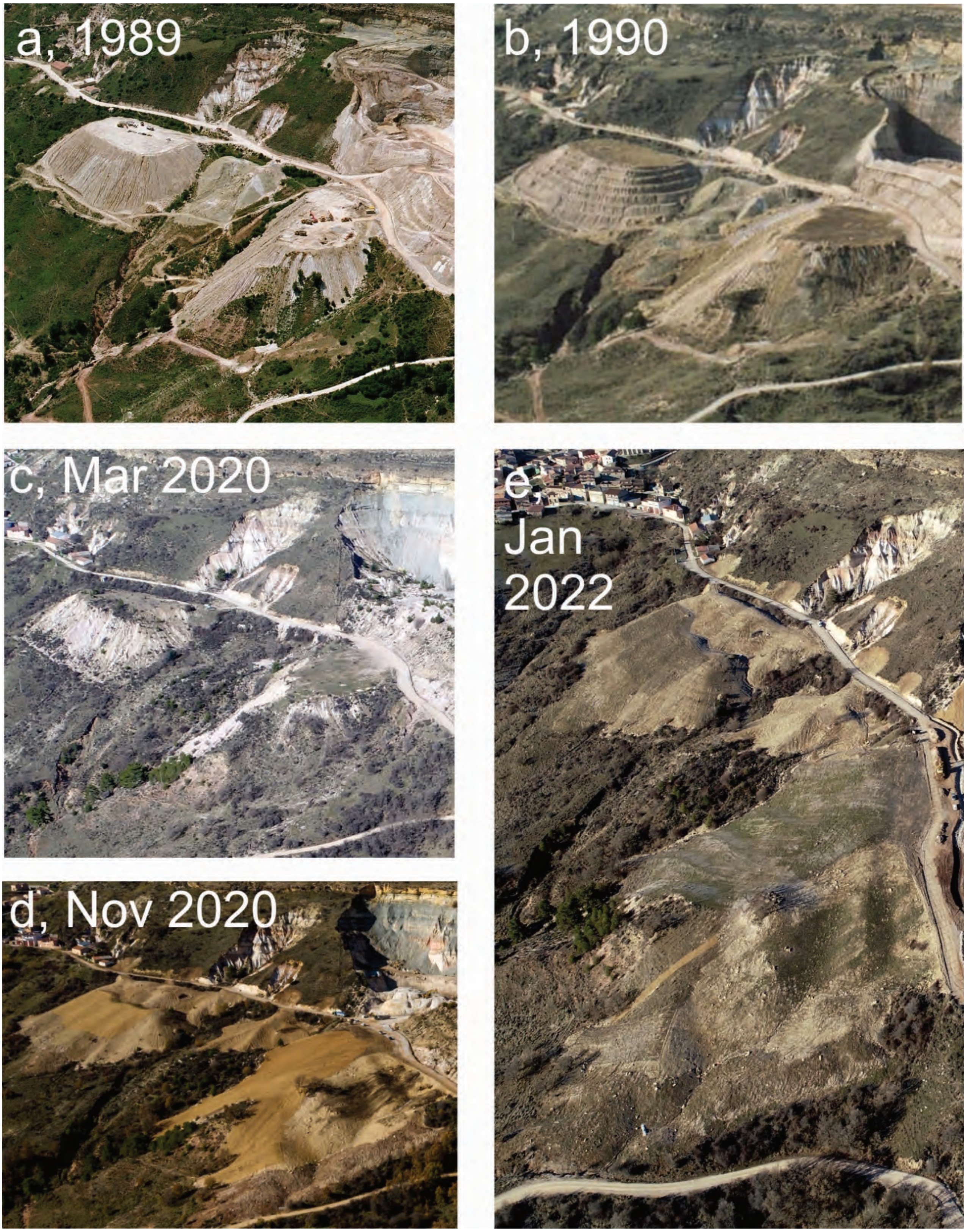

Figure 10 **Evolution of the external waste dumps of the Santa Engracia mine (Peñalén, Spain). (a) Scenario close to mine closure; (b) After initial rehabilitation (images by Paisaje Españoles); (c) After 30 years of erosion (image by DIEDRO); (d) After geomorphic regrading and organic mat installation (image by MA Langa); (e) After 1.5 years of new geomorphic-based intervention, showing stability against erosion (image by DIEDRO)**

Figure 11 **Evolution of the intervention area in Lousal (Portugal). The position of the rehabilitated area at the head of the artificial wetlands can be seen at the November 2021 photo. Photos by Bruno Gonçalves and Centro Ciência Viva do Lousal**

5 Indicators and monitoring

The improvement of the water quality downstream of the Santa Engracia mine (Peñalén, Spain) will be quantified by measuring the sediment emission-immission to water bodies. Erosion rate (sediment yield) at the Santa Engracia mine previous to LIFE RIBERMINE was 353 t ha^{-1} yr^{-1} (Martín-Moreno et al. 2018). The target values after restoration should range between 4 and 15 t ha^{-1} yr^{-1}, which (a) are already forecasted by the SIBERIA modelling (Hancock 2021) and (b) have been already measured by monitoring similar geomorphic-based solutions at nearby mines (Zapico et al. 2018). Regarding turbidity values, suspended sediment concentrations (SSC) at a pre-rehabilitation phase were 391 g l^{-1}, and target values (baseline) are 24 g l^{-1} (Zapico et al. 2017).

To monitor the sediment release from the rehabilitated areas, three check dams have been built to measure sediment yield (Figure 12a). A fourth check dam has been built in a nearby small watershed, not affected by mining, to show baseline conditions. The procedure is based on a similar experiment conducted by Bugosh & Epp (2019) in New Mexico (United States). For measuring SSC, we are using bottles with two lengths of bent plastic tubing (syphon) tied to a rigid framework to hold it in place (Figure 12b). The bottle starts to fill when the depth of flow reaches the lower plastic tube and ceases when the depth of flow rises to the higher point of the other tube, which is the outlet of the air exhaust pipe.

In order to assess the impact of the rehabilitation and remediation actions on the hydrochemistry of surface and groundwater in Lousal (Portugal), a series of both groundwater and surface water samples will be collected. Two sampling campaigns will be conducted annually during the two years of monitoring actions planned in the LIFE RIBERMINE project (2022–2024) and in the After-LIFE period (2024–2029). For groundwater monitoring, two piezometers have been installed (Figure 12c, d).

In each one of the water samples collected during the monitoring activities, the physicochemical parameters of the water (redox potential, pH, conductivity), the content of PTE (Pb, Cd, Zn, Fe and Cu) and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2+}, Cl^{-}, HCO_3^{-}) will be measured. The results obtained during the monitoring phase will be compared with those in the initial characterisation of the intervention area and the natural values of the environment to assess the reduction in water pollution. We expect that the AMD remediation actions applied in the intervention area are able to reduce the current PTE's maximum concentration values measured prior to the reclamation project. The values established by the Portuguese legislation for minimum water quality in surface waters (Pb – 0.05 mg/L, Cd – 0.01 mg/L, Zn – 0.5 mg/L, Cu – 0.1 mg/L) (Diário da República 1998) will be used as reference water quality values to evaluate the degree of success, and limitations, of the AMD remediation actions applied in the Lousal mine. We stress here that our intervention may have a limited effect, but since it is located at the head of the catchment, and it has a series of artificial wetlands downstream, is it expected to significantly improve the water quality of the Corona River system. The monitoring actions will confirm or refuse our hypothesis.

The effectiveness of the rehabilitation-remediation actions in Portugal will also be assessed by the determination of the heavy metal content of the riparian vegetation. To this end, starting from May 2022, and during two annual sampling campaigns, plant samples will be collected in the Lousal artificial wetland systems located downstream of the restored area, and outside the area of influence of the pollution, to assess the accumulation of heavy metals (Cu, Pb and Zn) and metalloids (As) over time. These results will be compared with those obtained prior to the reclamation action to evaluate the reduction in the content of PTE in the riparian vegetation.

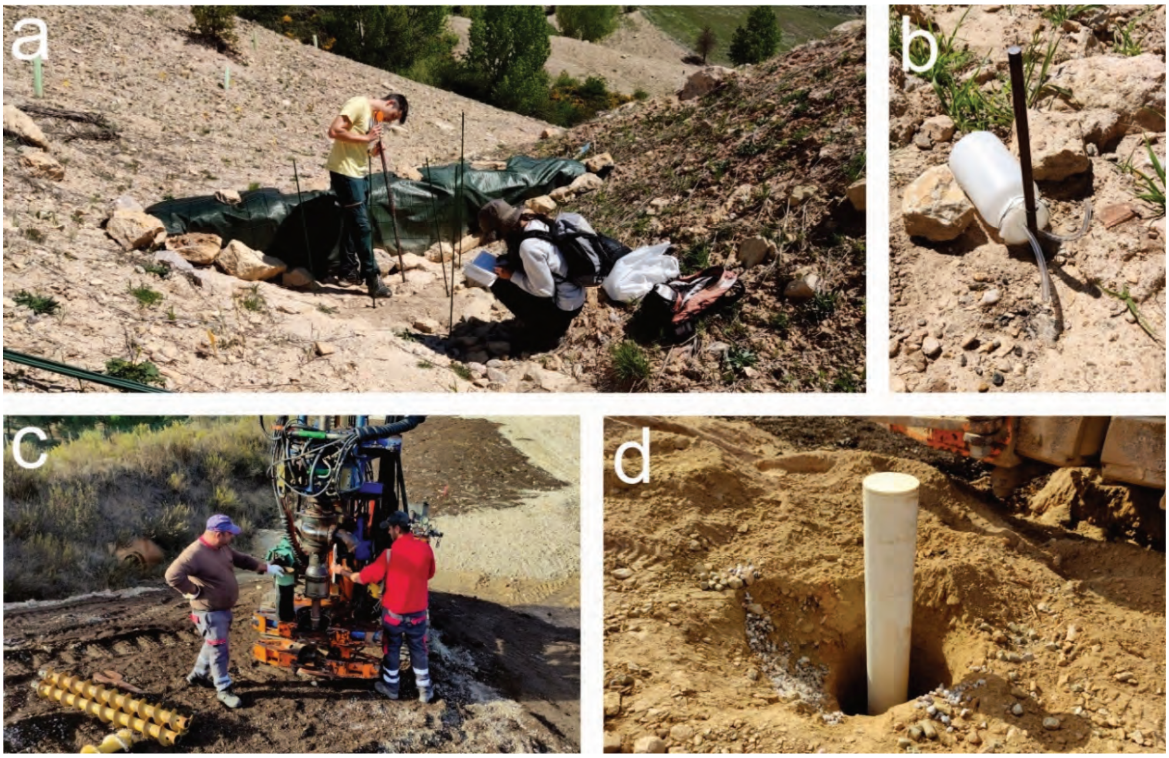

Figure 12 Monitoring procedures deployed to measure and quantify the improvement of water quality from the restored mined areas within LIFE RIBERMINE. (a) Check dams to measure total sediment yield (Peñalén, Spain); (b) Syphon bottles to sample SSC (Peñalén, Spain); (c) Installation of piezometer at Lousal (Portugal) to monitor water table and to take water samples; (d) Detail

6 Synthesis and concluding remarks

LIFE RIBERMINE describes mine closure actions in Spain and Portugal that integrate two GLD techniques: (a) GeoFluv–Natural Regrade for unconsolidated sandy waste dumps in Spain and pyrite deposits in Portugal, and (b) Talus Royal for hard-rock residual highwalls in Spain. SIBERIA LEM has been used to evaluate the erosional stability of post-mining GLD in Spain. AMD chemical stabilisation and remediation measures are combined with geomorphic landform designs in Portugal. Although there are other approaches and methodologies addressing similar objectives, LIFE RIBERMINE intends to implement an effective combination of them according to the problems to be addressed and to evaluate the potential spread of this strategy in Europe and elsewhere, if monitoring shows that they efficiently solve the tackled problems.

The deployment of those techniques, combined with proper soil recovery and revegetation practices is expected to significantly improve (as closer to baseline levels as possible) the water quality of the fluvial systems downstream of two polluted mines of the Iberian Peninsula. In Spain, the actions are expected to recover the fluvial ecosystems of the Tajo River, degraded by very high SSC coming from the Santa Engracia mine. In Portugal, the healing of the fluvial ecosystems of the Corona River, polluted by acid mine drainage formed by pyrite wastes of the Lousal mine, is the goal.

LIFE RIBERMINE aims to test the design, implementation and performance of the described techniques so they can be commonly applied to the mining industry, making them of robust and efficient use when they are needed. The performance results can be used to consider applying the innovative rehabilitation and remediation designs to other mine locations, abandoned or active, elsewhere. These project remedies are expected to reduce post-closure expense and liabilities. The most important outcome in this sense is that LIFE RIBERMINE techniques will be replicated at large-scale mine rehabilitation projects in Spain, within the so-called EU Recovery, Transformation and Resilience Plan (Next Generation EU funding).

Acknowledgement

The geochemical remediation content of this contribution is a small synthesis of a joint work performed by Ramón Sánchez-Donoso, José María Esbrí, Elena Crespo and M Luz García (UCM), Javier Lillo (URJC), Pablo Higueras (UCLM) and Monica Martins, Ana Margarida Pereira, Alvaro Manuel Madureira Pinto and Jorge Manuel Rodrigues de Sancho Relvas (Centro Ciência Viva do Lousal, Portugal). This paper is an outcome of the LIFE RIBERMINE (LIFE18 ENV/ES/000181) project. We thank Melanie Ball for her English-language editing of this manuscript.

References

BOE 2009, *Real Decreto 975/2009, de 12 de junio, sobre gestión de los residuos de las industrias extractivas y de protección y rehabilitación del espacio afectado por actividades mineras (Royal Decree 975/2009, of June 12th, for the management of waste from extractive industries and for protection and rehabilitation of sites affected by mining activities)*, BOE núm. 143, de 13 de junio de 2009 (BOE-A-2009-984), Ministerio de la Presidencia, Madrid, pp. 49948–49993.

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.

Diário da República 1998, *Decreto-Lei nº 236/98, de 1 de Agosto (Decree-Law nº 236/98, of August 1st)*, Diário da República, I Série-A. Nº. 176, 1-8-1998, Lisbon.

Diário da República 2010, *Decreto-Lei 10/2010, de 4 de Fevereiro (Decree-Law 10/2010, of February 4th)*, Diário da República Nº 24/2010, Série I de 2010-02-04, Lisbon.

European Council 2006, *Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the Management of Waste from Extractive Industries*. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2006L0021:20090807:EN:PDF

Ferreira da Silva, E, Bobos, I, Matos, JX, Patinha, C, Reis, AP & Cardoso Fonseca, E 2009, 'Mineralogy and geochemistry of trace metals and REE in volcanic massive sulfide host rocks, stream sediments, stream waters and acid mine drainage from the Lousal mine area (Iberian Pyrite Belt, Portugal)', *Applied Geochemistry*, vol. 24, pp. 383–401.

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

Hancock, G 2021, *Erosion Assessment of the Geomorphically Reconstructed Landscape at the LIFE RIBERIMINE Project. Phase 1 – External Waste Dumps, Santa Engracia Mine, Path to Poveda. Phase 2 - Path to Poveda (Pit and In-Pit Waste Rock Dump)*, unpublished reports, University of Newcastle, Callaghan.

Hancock, GR, Lowry, JBC, Moliere, DR & Evans, KG 2008, 'An evaluation of an enhanced soil erosion and landscape evolution model: a case study assessment of the former Nabarlek uranium mine, Northern Territory, Australia', *Earth Surface Processes and Landforms,* vol. 33, no. 13, pp. 2045–2063.

Hancock, GR & Willgoose, GR 2018, *Sustainable Mine Rehabilitation – 25 Years of the SIBERIA Landform Evolution and Long-term Erosion Model, From Start to Finish: a Life-Of-Mine Perspective*, Australasian Institute of Mining and Metallurgy, Melbourne.

Howard, EJ, Loch, RJ & Vacher, CA 2011, 'Evolution of landform design concepts', *Mining Technology. Transactions of the Institute of Mining and Metallurgy*, vol. 120, pp. 112–117.

Humphries, RN 1977, 'A new method for landscaping quarry faces', *Rock Products*, vol. 80, pp. 122H–122J.

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

IFC 2007, *Environmental, Health and Safety Guidelines for Mining*, International Finance Corporation, Washington.

Legwaila, I, Lange, E & Cripps, J 2015, 'Quarry reclamation in England. A review of techniques', *Journal American Society of Mining and Reclamation,* vol 4, pp. 55–79.

Luís, AT, Teixeira, P, Fernandes Pinheiro Almeida, S, Matos, JX & Ferreira da Silva, E 2011, 'Environmental impact of mining activities in the Lousal area (Portugal): Chemical and diatom characterization of metal-contaminated stream sediments and surface water of Corona stream', *Science of the Total Environment,* vol. 409, pp. 4312–4325.

Martín Duque, JF, Tejedor, M, Martín Moreno, C, Nicolau, JM, Sanz Santos, MA, Sánchez Donoso, R & Gómez Díaz, JM 2020, 'Geomorphic landscape design integrated with progressive mine restoration in clay quarries of Catalonia', *International Journal of Mining, Reclamation and Environment*, vol. 35, no. 6, pp. 399–420.

Martín Duque, JF, Zapico, I, Bugosh, N, Tejedor, M, Delgado, F, Martín-Moreno, C & Nicolau, JM 2021, 'A Somolinos quarry land stewardship history: From ancient and recent land degradation to sensitive geomorphic-ecological restoration and its monitoring', *Ecological Engineering*, vol. 170, 106359.

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.

Ministerio de Minería 2011, *Ley 20551, Regula el cierre de faenas e instalaciones mineras (Regulating the Closure of Mine Activities and Installations),* Biblioteca del Congreso Nacional de Chile, Valparaíso.

Minister of Public Works and Government Services Canada 1996, *The Minerals and Metals Policy of the Government of Canada*. Partnerships for Sustainable Development, Catalogue no. M37- 37/1996E. Minister of Public Works and Government Services: Quebec.

NMMMD 2010, *A Method for the Evaluation of Compliance with the Approximate Original Contour Requirements of CSMC RULE 19.8. NMAC*, New Mexico Mining and Minerals Division, Santa Fe, http://www.emnrd.state.nm.us/MMD/\ documents/AOCGuidelines.pdf

Oliveira, M, Ferreira, T, Relvas, JMRS, Pinto, AMM, Pereira, Z, Matos, J & Fernandes, C 2013, 'Lousal, Portugal: Geologic and mining heritage of an ancient mine from Iberian Pyrite Belt', in *Actas del XIV Congreso Internacional sobre Patrimonio Geológico y Minero*, Sociedad Española para la Defensa del Patrimonio Geológico y Minero.

Sánchez-Donoso, R, García Lorenzo, ML, Esbrí, JM, García-Noguero, EM, Higueras, P & Crespo, E 2021, 'Geochemical characterization and trace-element mobility assessment for metallic mine reclamation in soils affected by mine activities in the Iberian Pyrite Belt', *Geosciences,* vol. 11, no. 233.

Willgoose, GR & Riley, S 1998, 'The long-term stability of engineered landforms of the Ranger Uranium Mine, Northern Territory, Australia: application of a catchment evolution model', *Earth Surface Processes and Landforms,* vol. 23, no. 3, pp. 237–259.

Zapico, I, Laronne, JB, Martín-Moreno, C, Martín Duque, JF, Ortega, A & Sánchez-Castillo, L 2017, 'Baseline to Evaluate Off-site Suspended Sediment-Related Mining Effects in the Alto Tajo Natural Park, Spain', *Land Degradation and Development,* vol. 28, pp. 232–242.

Zapico, I, Martín Duque, JF, Bugosh, N., Laronne, JB, Ortega, A, Molina, A, Martín-Moreno, C, Nicolau, N & Sanchez Castillo, 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.