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Drainage network evolution and reconstruction in an open pit kaolin mine at the edge of the Alto Tajo natural Park

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ABSTRACT

Landform instability of the abandoned Nuria kaolin mine, surrounding the Alto Tajo Natural Park in Spain, has caused frequent and severe environmental impacts due to deficient mining practices, environmental mismanagement and closure planning. Geomorphic instability has caused widespread soil erosion and elevated sediment yields with off-site effects. We quantified such land instability, the evolution of the resulting drainage networks and catchments, and ensuing gully processes. High Resolution Topography sources were compared with historic maps and photos. The current mine rehabilitation practices are depicted based on a geomorphic approach that introduces a sustainable drainage system designed to avoid detected risks. Our aim is reconstructing fluvial channels and related hillslopes that mimic their natural counterparts adapted to a rehabilitation of pre-existing gradient terraces. We demonstrate that: i) mining activity produced a 31–58% decrease in the original site drainage network ii) a post-mining active advancing gully is an indicator of drainage network redevelopment advancing toward an upstream pond with flash-flooding risk; iii) a geomorphic designed and constructed fluvial network and proper drainage density adapted to pre-existing gradient-terraces seeks reestablishing stability; and iv) in absence of sufficient funding for rehabilitation, public/private collaboration agreements play an important role to reinstate landscape stability of abandoned or erroneously restored mines.

1. Introduction

Mining is essential for human activities. Nevertheless, it is responsible for many environmental impacts due to the processes of extraction and processing. It disturbs not only the land where it is developed, through the loss of landforms, soil, vegetation and fauna, but also impacts the downstream landscape with its polluted spillages (Mossa and James, 2013; Tarolli et al., 2018). Increase in stormwater runoff and sediment yield from mining areas has been widely documented (Katpatal et al., 2017). Several environmental land management control measures apply to mine operations and can often be achieved in parallel to modern mining activities. However, a major challenge arises at the end of mining operations, when a closure plan to permanently stabilize and rehabilitate the mined area, including its facilities, is enforced. At this stage, owners are required to minimize possible future land degradation and social impacts. Actions of post-mining environmental mitigation are expensive and can delay the release of the mining bond. Closure plans integrated with mining operations provide best stability and environmental results at the cheapest cost (Hannan, 1984). In many cases, by lacking this integration, the unsuccessful rehabilitation areas cause severe environmental impacts (Reed and Kite, 2020).

Stability issues causing damages and pollution in rehabilitated areas often occur due to erosion vulnerability of traditional straight shapes of the constructed landforms, and because the rigid erosion control structures are unable to manage runoff in the long term, thereby generating erosion of hillslopes and ditches (Sawatsky and Beersing, 2014). For instance, in a rehabilitation study of three West Virginian mines, a drainage network that did not reproduce natural analogues in terms of density and bankfull geometry was the main factor causing severe gully erosion and landslides (Kite et al., 2004). Whereas that multi-temporal

Abbreviations: DEM, Digital Elevation Models; DoD, DEMs of Difference; SfM, Structure from Motion; UAV, Unmanned Aerial Vehicle; LiDAR, Light Detection and Ranging; GCD, Geomorphic Change Detection; ALS, Aerial Laser Scanning; HRT, High Resolution Topography.

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study utilized topographic maps and conventional GPS, the number, length of gullies and landslide frequency were recently examined in reclaimed central Appalachia using Light Detection and Ranging (LiDAR) data from a single date (Reed and Kite, 2020). They also interpreted how these erosion shapes appeared due to faulty rehabilitation practices, such as retention cells in the upper part of the terraces. These valuable studies draw attention to damages incurred due to lack of shaping a proper drainage network. However, long-term studies combining both multi-temporal analyses and accurate topographic data are required to improve quantification of erosional stability (Reed and Kite, 2020).

Recovering long-term terrain stability extends thinking beyond structures such as ditches, dumps and ponds, to designing and constructing functional landscapes with streams, hillslopes or wetlands that function independently based on hydrologic conditions (McKenna and Dawson, 1997). Such features have to be organized as self-regulating erosional catchments (Stiller et al., 1980). In this context, Fluvial Geomorphic Rehabilitation based on a surficial drainage management (Bugosh and Epp, 2019), with specific methods such as GeoFluv-Natural Regrade (Bugosh and Epp, 2019; Zapico et al., 2018), is a proliferating rehabilitation technique to achieve long-term erosion stability of land disturbed by mining. This methodology has been catalogued as a Best Available Technique for the management of waste from extractive industries in accordance with the European Directive 2006/21/EC (Martin Duque et al., 2019). It can also be used in combination with Landscape Evolution Models such as SIBERIA, to evaluate the stability of designs and successively improve them (Hancock et al., 2019). Several fluvial geomorphic mine-rehabilitation examples exist in the United States (Bugosh and Epp, 2019) and Spain (Zapico et al., 2018). In those cases, this approach reinstated functional landscapes, which correspond site erosion values to those of the surrounding natural landscapes (baseline), inclusive of successful stabilization of a landslide (Zapico et al., 2020). This accomplishment derives from the introduction of a drainage density similar to natural reference landscapes and designing as well as constructing fluvial channels with similar longitudinal and cross-sectional shapes as the natural ones. Indeed, such criteria are required in credible landscape engineering (McKenna and Dawson, 1997).

Today, worldwide mine rehabilitation is still dominated by a focus on soil and vegetation management. In most countries, this focus is fostered by regulations, seeking that mine rehabilitation require “safe, stable, non-polluting post-mining landforms”, as in Australia (Howard et al., 2011). However, a growing body of literature (e.g., McKenna and Dawson, 1997; or Kite et al., 2004) has demonstrated that, without a proper consideration of natural drainage systems in mine rehabilitation, instability occurs. The United States Surface Mining Control and Reclamation Act (SMCRA, 1977) was the pioneering law regarding mine rehabilitation, demanding that the extent to which surface configuration achieved by backfilling and grading of a mined area must closely resemble the general surface configuration of the land prior to mining, and should blend into, and complement the drainage pattern of the surrounding terrain. It is surprising how, 44 years later, it is still the only mine rehabilitation law, worldwide, with such focus. Thus, although the example we provide is site-specific, it shows a contribution with global implications, at the least for fluvial processes, acting on the overwhelming majority of the ice-free land surface.

Detailed topographic monitoring is required to understand and manage drastic landscape modifications due to mining and rehabilitation practices (Ross et al., 2016). Some of these evaluations are undertaken by comparison of topographies. In earth science, the most common methodology to quantify topographic change is Geomorphic Change Detection (GCD) through Digital Elevation Models (DEMs) of Difference (DoDs); its use in mining projects is increasing (Xiang et al., 2018; Zapico et al., 2018). Traditionally, topographic surveys are undertaken with differential GPS (dGPS), Total Station, Terrestrial Laser Scanning or Aerial Laser Scanning (ALS). However, an emerging technique, Structure from Motion (SfM) combined with Unmanned Aerial Vehicles (UAVs), SfM-UAV, is replacing these technologies due to its ease of use, lower cost and high accuracy and resolution (Carrivick et al., 2016). In mining areas SfM-UAV is used to study mining stability (López-Vinielles et al., 2020) and to monitor mining activity (Carabassa et al., 2020). Historically, most mining areas were sanctioned, such that early site data based on modern topographic techniques are typically unavailable. In those cases, studies can be completed with historic topographic maps (Zapico et al., 2020).

The primary Spanish kaolin extraction is undertaken in an area surrounding one of the most biodiverse natural parks in Spain, the Alto Tajo. Here, abandoned mines cause severe impacts on the natural fluvial system. They experience risky landslides and produce high sediment yields (Zapico et al., 2017), arising due to their unstable landforms and lack of erosive-sedimentary control measures (Martín-Moreno et al., 2018). The Nuria mine is one such abandoned operation. It was closed because extension of a new concession was rejected, due to faulty environmental performance and an inadequate closure plan. Therefore, the bond release was not returned to the owners. This guarantee was used to stabilize a rotational landslide in a waste dump using geomorphic rehabilitation (Zapico et al., 2020). Other unstable areas continue posing risks, and several monitoring, analysis and stability measures are being accomplished through agreements of public and private collaboration. Using High Resolution Topographies (HRTs), a historic topographic map and photos, the evolution of an existing drainage network, its catchments and a gully were studied. Fluvial Geomorphic Rehabilitation is proposed as a technique to stabilize the detected instabilities in the Nuria mine. Our aims are to: i) qualify and quantify the temporal change in drainage network density and catchment changes due to mining activity and rehabilitation practices; ii) quantify the main current erosive gully processes threatening mine stability; iii) describe the versatile application of a geomorphic rehabilitation to an unstable waste dump requiring innovative adaptation to preexistent-terraces; and iv) discuss the importance of public-private collaboration to solve environmental problems in abandoned or deficiently restored mines.

2. Material and methods

2.1. Study area

2.1.1. The Alto Tajo natural Park

The Alto Tajo Natural Park is a well-known Spanish protected area formed by a dense network of fluvial canyons with steep and long slopes geologically incised by the Tajo River and its tributaries. The main feature is the high-quality water of its fluvial system and the ecosystems that it supports. The best national kaolin has been extracted during the last decades at four mines surrounding the park (Fig. 1). The Nuria and the Santa Engracia mines are now abandoned; sediment yield from these mines is considered by the natural park managers as the main environmental risk to the Alto Tajo Natural Park. The lack of proper erosion control measures leads not only to adverse on-site impacts, but also to off-site effects. Two other active mines, the Machorro and the María José, are well-known for applying remedies: maintained sedimentation ponds (Zapico et al., 2021) and geomorphic rehabilitation (Garbarino et al., 2018).

2.1.2. History of the Nuria mine

The Nuria mine occupies an oval-shaped structural valley, with the pointed side facing the southeast. The valley is open towards the northwest by the erosion of two main drainage lines: the Matalascabras stream and the Carrascalejo creek, both sub-catchments of the Tajuelo stream, a tributary of the Tajo River (Fig. 1). The valley sides are formed by typical scarps of the mesas, cuestas and hogbacks that surround the valley. The bottom valley is excavated in Jurassic limestones and Cretaceous sands, silts and clays (Weald facies); the valley walls are shaped in silica and kaolinite sands (Utrillas facies). The Carrascalejo creek lacks a proper fluvial headwater, which is cut by the

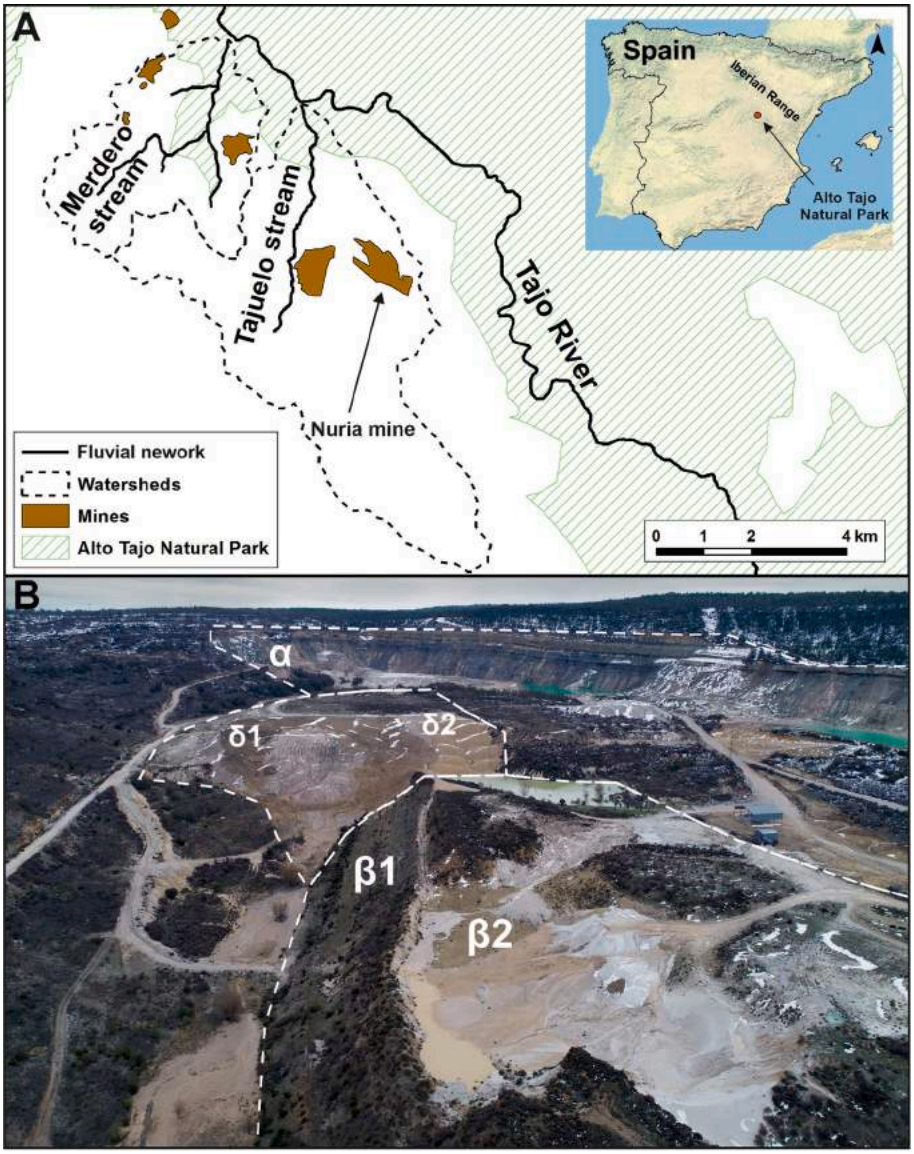

Fig. 1. Location of the Alto Tajo Natural Park and the Nuria mine (A), and oblique view of the Nuria mine on 15.04.2018 (B). Redrawn from Zapico et al. (2018). The mine is classified into three areas: "α" an open pit with three ponds near the highwall base; "β" an altered terraced waste dump to reprocess its wastes ("β1" part of the terraces not modified and "β2" part of the terraces removed); and "δ" a terraced waste dump that experienced a landslide and severe erosion, thereafter stabilized ("δ1") and restored ("δ2") with geomorphic rehabilitation. Photos by DGDRONE (2018).

Matalascabras valley. This is clear evidence of an ancient stream capture, in which the upstream erosion of the Matalascabras catchment captured the Carrascalejo headwaters.

Mining operations started here approximately in 1982 and initially the mine was adequately rehabilitated. This resulted in a series of terraces, built as progressive rehabilitation ("β" zone in Fig. 1) over 30 years, that have been mostly stable, and are now successfully colonized by vegetation. However, a change of owner brought cessation to mine rehabilitation. Furthermore, some restored areas were either buried with new waste dumps or modified. Due to incorrect environmental performance and an inadequate closure plan, a new concession extension was rejected, and the bond release was not returned to the owners. The 'final' scenario of the Nuria mine, when extractive activity was ended by the regulators in 2010, was a very heterogeneous site, with rehabilitated areas coexisting with large tracts lacking measurements of recovery. Hence, mass movements and gullying have progressed, generating risky situations, such as active landslides and potential flash flooding. The situation at the end of the activity was as follows (Fig. 1):

- "α" zone. The open pit and three ponds located at the highwall base were left without rehabilitation measures or proper drainage systems. Two of the ponds were excavated on original ground and the third, located most upstream, was formed with an earth dam of unconsolidated and sorted sand. This is causing two main risks: i) gully and ravine erosion processes are redeveloping the drainage network, advancing towards a series of ponds located at the highwall foot; and, ii) three ponds are accumulating a large amount of water, so the hazard of dam failure or spilling if captured by gully headcutting has a potential risk to cause harmful flash floods.
- "β" zone. These are the oldest terraces constructed in the first stages of the mine by the original owners. In the absence of significant erosion, vegetation has grown ("β1"), to successful rehabilitation, with some uncertainty about long-term stability. However, parts of the highest terraces were modified by the last owner to reprocess waste material "β2". At the end of this activity, the waste material was left at the top of the terraces, has been exposed to erosion and is threatening the stability of the entire rehabilitation.
- "δ" zone. A waste dump restored by gradient terraces constructed over part of the terraces in "β" zone and over the center of a valley, obstructed drainage in the natural ephemeral channel. It experienced a large rotational landslide ("δ1") and severe erosion ("δ2"). During 2014–2017 these were stabilized and rehabilitated (Zapico et al., 2020).

2.2. Topographic sources and analyses

Four types of topographic sources were used (Table 1): i) a 1:25,000 topographic map with 10 m equidistant contours (IGN, 1995); ii) two high resolution LiDAR point clouds covering the entire mine were surveyed by ALS and provided by the Spanish National Plan for Aerial Orthophotography (PNOA, 2018, 2009); iii) a drone paired with an SfM image processing (SfM-UAV) survey for the "β" zone; iv) a point cloud surveyed with a Leica 1200 dGPS. The SfM-Survey was performed in 2018 with 487 photographs taken at zenithal and oblique angles by a DJI Phantom 4 Pro drone kept at a constant altitude with a maximum height of 120 m above ground. The Ground Sample Distance (GSD) was 3.09 cm pix^{-1} and the final pixel error was 0.2. Altogether 30 targets were placed as check (11) or control points (19). The targets were measured with the dGPS. Photographs and control points were processed with Agisoft PhotoScan software. The main parameters used in this software were: alignment accuracy, Highest; key point limit, 40,000; Tie point limit, 4,000; dense point cloud quality, High; Filter mode, Aggressive. Vegetation was 'cleaned and check points were used to measure the accuracy using the LP360 Advanced edition software (Qcoherent, 2018).

The topographic map and the two LiDAR-ALS data were used to delineate catchments and the drainage networks before and after the Nuria mine appearance by using an automatic catchment and stream delineation procedure in ArcGIS Pro 2.5.1 (ESRI, 2020). These drainage networks were also reviewed and corrected as needed, using the more recent public orthophotos for each topographic source and photo interpretation. Drainage network lengths were associated with the mining catchment area to define the temporal evolution of drainage density evolution. Channels of each drainage network were classified into four types: i) original, before mining activity; ii) unpaved road ditches built by the mining operators; iii) gullies developed due to fluvial erosion; iv) drainage systems equivalent to natural ones introduced by Fluvial Geomorphic Rehabilitation. A field campaign for ground truthing was conducted on March 17, 2021 to evaluate the digitization quality of the drainage network. The head and mouth locations of some channels were surveyed with dGPS. Assuming dGPS data as true control points, we estimate the accuracy of our digitalization by calculating the root mean square error (RMSE). Since the last public topography covering the entire mine dates to 2018 (Table 1), we measured head and bottom locations in those channels experiencing no change between 2018 and the present. Check points are shown in Fig. 3. We conclude that our digitalization has an average planimetric accuracy of 9 m.

The two LiDAR-ALS topographies were also used to analyze the most critical site in terms of geomorphic instability in the "α" zone. They were transformed to DEMs and a comparison between them through a DoD was obtained using the GCD methodology (Wheaton et al., 2010) and software (GCD, 2018) to calculate the earth eroded in terms of volume, depth and upstream migration. DoD analyses produced volume data and images of erosion-deposition zones. Having detected the rapid evolution of the referred gully area, a final survey with dGPS was carried out over the main active gullies in 2020 and was also processed with GCD software. The SfM-UAV topography survey obtained on 15.04.2018 was used to obtain the base topography for the geomorphic design of the "β" zone.

Table 1
Topographic data availability and related accuracy.

Date	Source/method	Photos	Point cloud density	RMSE check points		
				nº	x,y	z
		#	pts m^{-2}	#	m	
19,84[1]	25,000 topographic map with 10 m equidistant contour	n.d.	n.d.	n. d.	n.d.	1.93[2]
02.02.2010	LiDAR-ALS	n.d.	0.5	n. d.	0.3[3]	0.2[3]
29.06.2018		n.d.	1	n. d.	0.3[3]	0.2[3]
15.04.2018	SfM-UAV	487	373	11	0.14	0.04
17.04.2020	dGPS	n.d.	0.09	n. d	0.03[4]	0.03[4]

n.d. - no data.
[1] This map was published in 1995 and prepared with photogrammetric data dated 1984.
[2] Derived from a direct comparison with 2009 topographic data of those areas without topographic changes between the two dates.
[3] technical specification (PNOA, 2018, 2009).
[4] local accuracy was not measured for the points surveyed with the DGPS. We adopt values reported elsewhere using a similar instrument (Cucchiaro et al., 2018; Lucieer et al., 2014).

2.3. Fluvial geomorphic rehabilitation

A geomorphic approach was used to rehabilitate the damaged terraces in zone "β2". Since some sectors of zone "β1" terraces have not shown a significant sign of erosion (Fig. 1), the geomorphic design is to be selectively adapted to these pre-existent terraces. Hence, a mixed (hybrid) approach is applied to this case: the external terraces were rebuilt (1.5 ha) and a geomorphic design based on the GeoFluv method and the Natural Regrade software was planned for the highest part (3.6 ha).

3. Results

3.1. Temporal catchment and drainage network evolution in the Nuria mine

The Nuria mine, located in the intermediate part of two subcatchments of the Tajuelo stream, drained water from 449 ha before mining activity ensued. These natural catchments thereafter drained 62% of the catchment, the remaining area forming two endorheic subcatchments draining to ponds located at the bottom of the pits at the highwall toe (Fig. 2). The drainage network developed in three stages: before the mining activity in 1984 at the pre-mining stage; near the end of mining activity during 2009–2010 with the drainage network based on ditches and gullies; and, after eight years that natural processes shaped the drainage network and undertaking three geomorphic stabilization/rehabilitation projects (Fig. 3 and Table 2). In 1984 the drainage network had a fourth stream order and a typical dendritic shape. It was modified by the mining activity, which removed the upper part of the network and introduced straight artificial drainage ditches mainly at the edges of the mine. Some gullies also appeared within zones having no drainage. In 2018 new gullies grew and others were stabilized by geomorphic rehabilitation, reshaped into new fluvial channels with zig-zag and meandering shapes, based on local natural analogues (Zapico et al., 2020).

3.2. Headcutting gully erosion migrating towards the ponds

Although several efforts were undertaken to rehabilitate and stabilize the Nuria mine in zones "β" and "δ", a significant surface, zone "α", remained unstable. Here, frequent rilling and gullying erosion caused watercourse damage, producing high sediment yields and threatening the stability of the mine. The most hazardous zone is located downstream of one pond (yellow channels on the bottom right of Fig. 3C). Here, a road was dissected by the headcut migration of a knickpoint, initially advancing from the road ditch toward a series of ponds located at the base of a highwall (Fig. 4).

This gullying of the mine roadway was quantified by using the 2010–2018 LiDAR-ALS topographies (Fig. 5). The knickpoint advanced 25 m during 7.5 years having a 1.3 m average depth, maximum 2.5 m. This gully advanced an annual average rate of 3.3 m during the

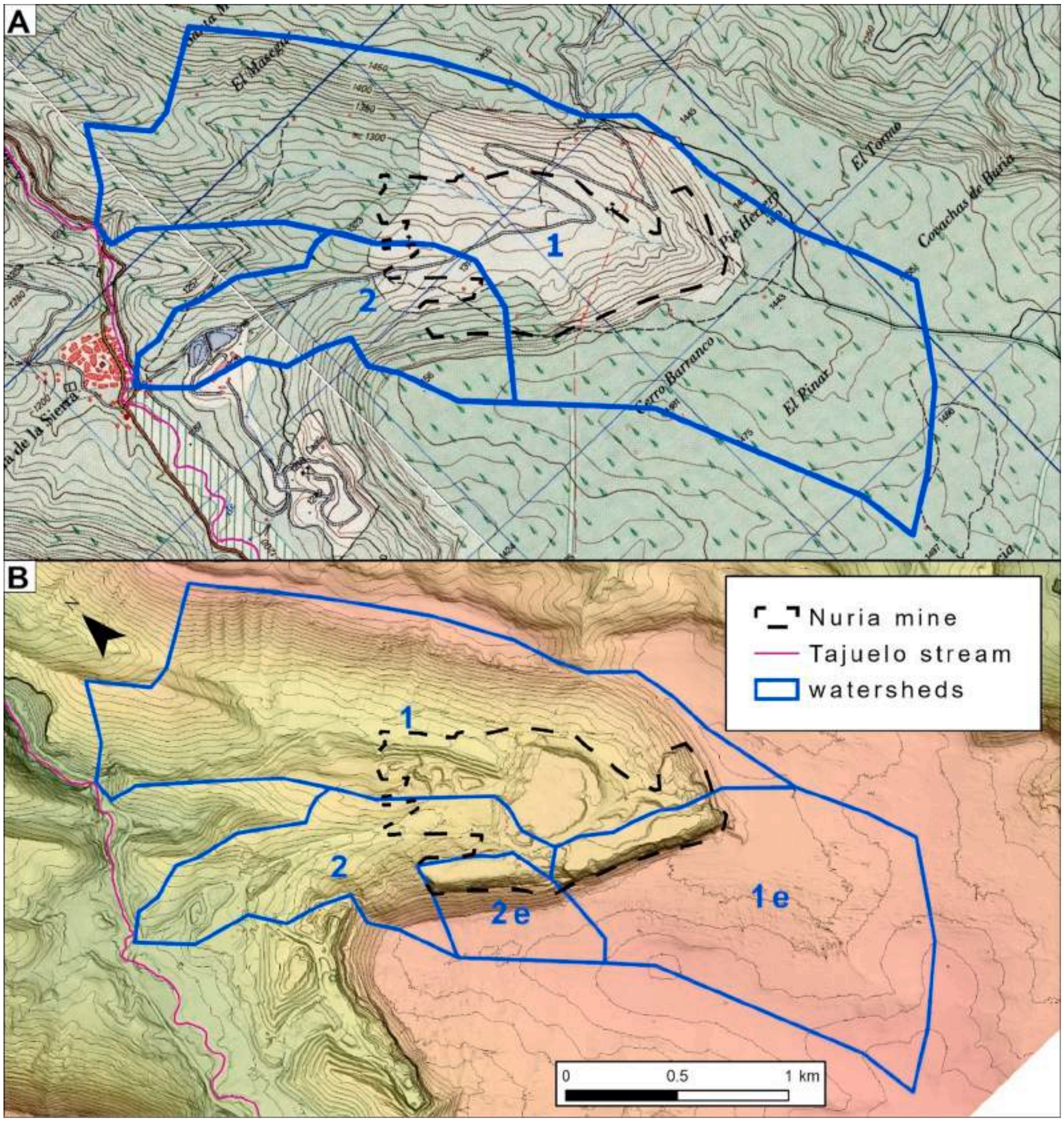

Fig. 2. Catchment evolution in the Nuria mine: (A) 1984, before mining; (B) 2018, after mining; (1, 2) natural catchments; (1e, 2e) mining-modified endorheic catchments with ponds at the highwall toe. A 25,000 map and a DEM and contours are the background for each date.

measurement period. This process can be clearly identified in the profiles of Fig. 6. Considerable (400 m^3) sediment was eroded from the road, of which 300 m^3 were deposited in a downstream ditch. The remaining sediment was transported downstream.

To reassess the high erosive activity which took place between 2010 and 2018 (Fig. 5), a new survey was conducted in 2020. The comparison between the 2020 and 2018 topographies shows that the left gully knickpoint (Fig. 5, B) advanced 53 m with a 0.8 m average depth, resulting in a 26.5 m/yr average biannual advance. This gully activity caused considerable (261 m^3) erosion and deposition (64 m^3), transporting 197 m^3 of sediment downstream.

3.3. Sustainable drainage system reconstruction

A detailed topography was surveyed using the SfM-UAV procedure (Fig. 7) to represent the initial condition of the area. A geomorphic design was generated for the upper part of the non-reclaimed area (Fig. 8) based on that topography and the parameters measured in a local natural analogue. The channels have a zig-zag (slope > 4%) and meander (slope < 4%) shapes; convex-concave hillslopes and concave swales were added to the design. One channel is tributary to another, ending in a pond that operates as base level. The channel slope varies (0–13%); the entire reclaimed area has an average 22% slope. The external terraces were also designed to be adapted to the surrounding hillslopes (Fig. 7). The original terraces were very steep (50–60%), whereas those designed are gentler (30–45%). Berm width varies in the range 7–13 m, having an 8% inverted gradient. This inverted gradient berm is a key issue for terrace preparation, preventing water flowing from the next slope, thereby triggering rill and gully erosion.

The project area will be finalized by spreading a 1-m depth of carbonate colluvium and 20 cm of topsoil. These thicknesses will be larger for the terraces, 2 m and 1 m respectively, owing to their higher gradient. The surface will be seeded with a mix of local herbaceous ground cover and shrubs. The rehabilitation started in the middle of 2018 and currently the third terrace is almost finished. Once terrace construction ends, the final geomorphic design will be built with proper equipment (an excavator and a D6 bulldozer). Altogether 190,000 m^3 of waste material, 57,000 m^3 of carbonate colluvium and 14,500 m^3 of topsoil will be used in the rehabilitation.

4. Discussion

Here we first-ever carried out a full multi-temporal study of the evolution of the drainage network density in a reclaimed mining area

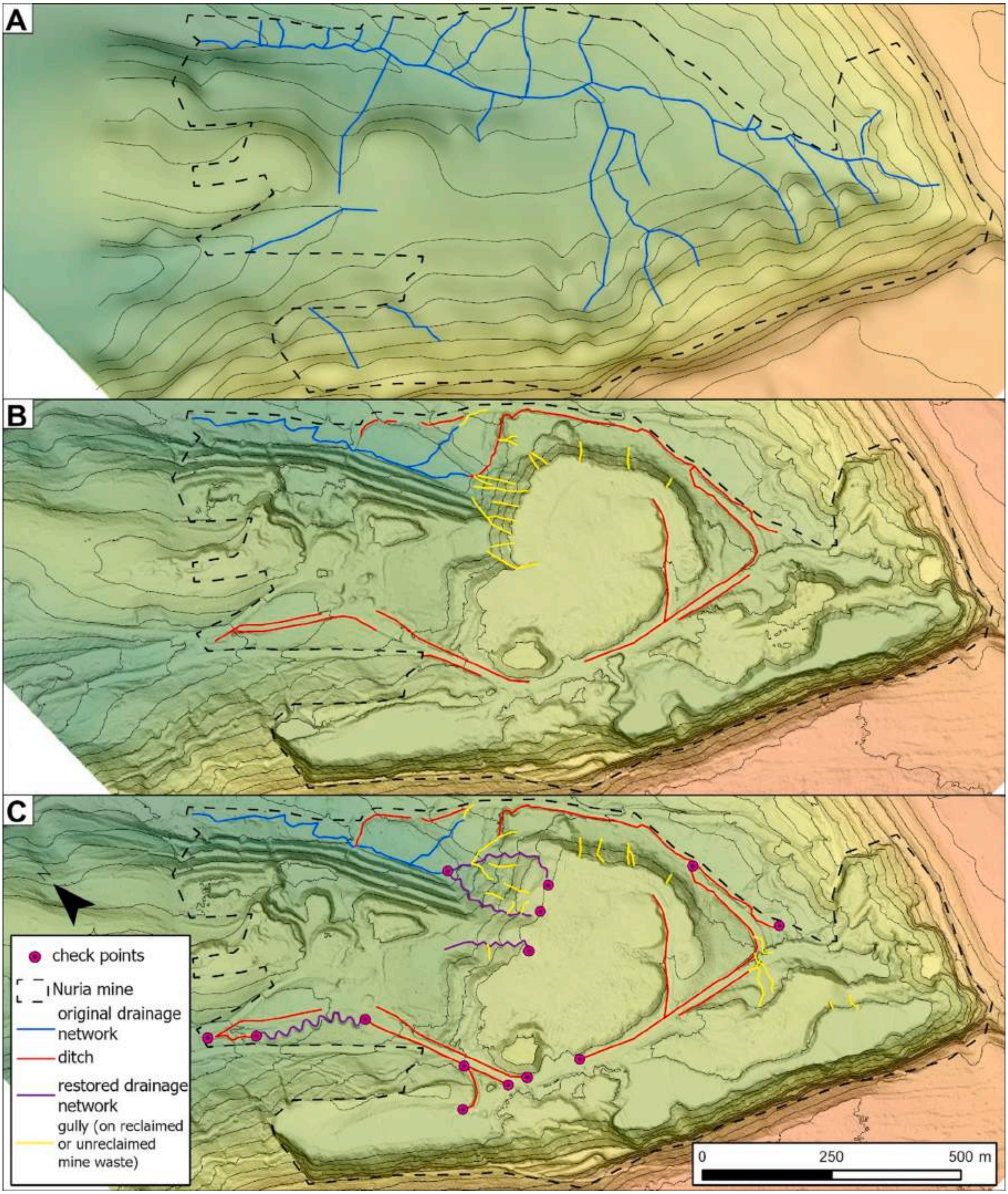

Fig. 3. Temporal change in drainage network and type of drainage lines around the Nuria mine: (A) 1984, (B) 2010 and (C) 2018. A DEM and contours are the background for each map.

with historic maps and HRTs. We also quantified the magnitude of the main gullying process of the mine, showing how the absence of proper drainage density produces areas prone to flash flooding and landslides. We also propose to restore an unstable area by creating a functional catchment with natural shapes, including concave channels and convex-concave hillslopes, with the novelty that it is adapted to a restored terraced area.

4.1. Long-term catchment and drainage network evolution

Topographic transformations always occur in mined areas. Among these, drainage layouts can be disturbed by changing the spatial pattern of divides, either forming endorheic basins, or modifying the main and secondary divides. The Nuria mine exemplifies this impact: prior to mining this valley had a subtle divide between the Matalascabras and the Carrascalejo valleys. Mining displaced this intra-valley divide while the excavation at the foot of the mine highwall created endorheic basins draining to several artificial ponds at the bottom of the pits (Fig. 2).

Table 2
Temporal variation of drainage network length and density in the Nuria mine.

	1984			2010			2018		
	length		density	length		density	length		density
	m	%	m ha^{-1}	m	%	m ha^{-1}	m	%	m ha^{-1}
original (natural) drainage network	5,360	100	67	756	17	10	735	13	9
artificial ditches	0	0	0	2,910	64	36	2,950	53	37
restored drainage[1]	0	0	0	0	0	0	973	18	12
gully[2]	0	0	0	872	19	11	905	16	11
total	5,360	100	67	4,540	100	57	5,560	100	69

[1] drainage network by Fluvial Geomorphic Rehabilitation.
[2] on reclaimed or unreclaimed mine waste.

Fig. 4. Gully erosion cutting one of the roads in the Nuria mine. (A) knickpoint (b) migrating upstream (January 2016) and (B) erosion bisecting the road (February 2017). (a) the position of a wooden pole is used as reference. Modified from Hancock et al. (2020).

These endorheic catchments retain water from more than one third of the pre-mining area affected by the Nuria mine.

Despite the addition of ditches, mining activity decreased the pre-mine drainage density (from 67 to 46 m ha^{-1}—altogether a 31% reduction excluding gullies) by obliterating most of the drainage network. This magnitude of reduction 18–84% depending on the studied catchments, was also documented elsewhere (Kite et al., 2004). Such a reduction in drainage density could be larger, because agricultural practises conducted prior to the 1984 source map 'erased' a portion of the original natural drainage lines, by filling the head of channels. However, the magnitude of this underestimation is unknown. Sánchez-Donoso et al. (2020) estimated 5–7% reductions by this factor. The pre-mine drainage density also reflects a drainage development on

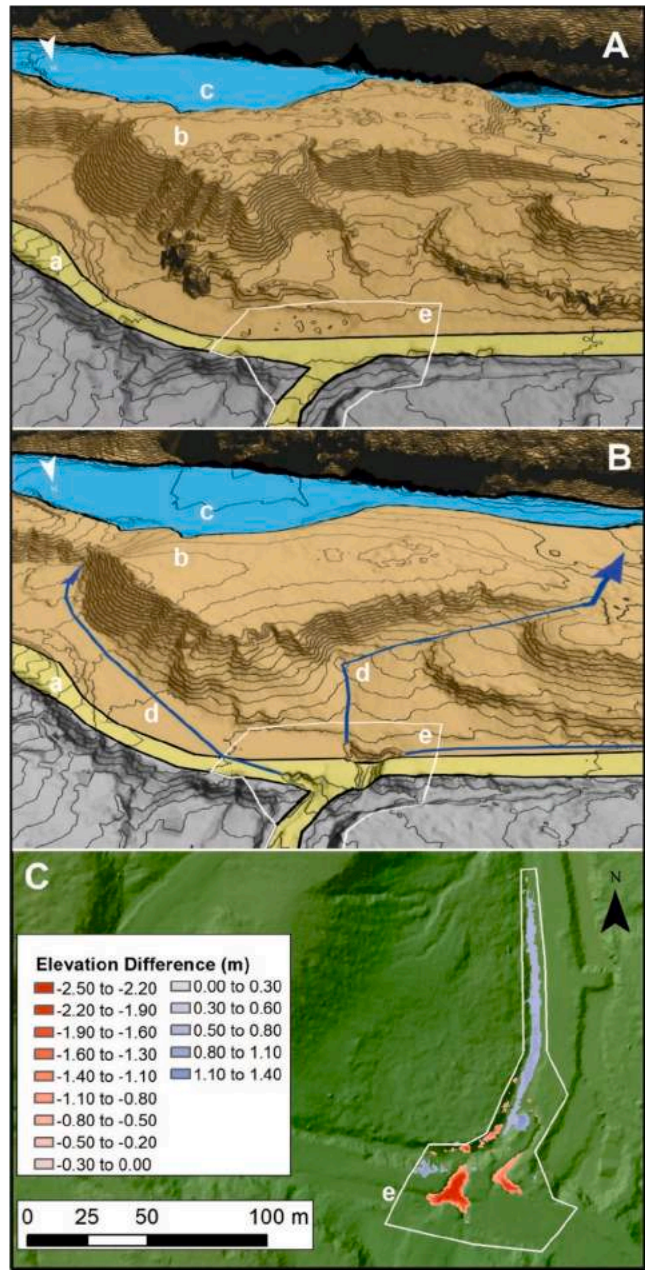

Fig. 5. Topography before (A, 2010) and after (B, 2018) gully development. (C) DoD showing (a) unpaved road; (b) area between the ponds and the unpaved road; (c) pond; (d) likely evolution of gully erosion; (e) polygon used to calculate the DoD in the gullied area. The arrows in B show the direction of knickpoint migration.

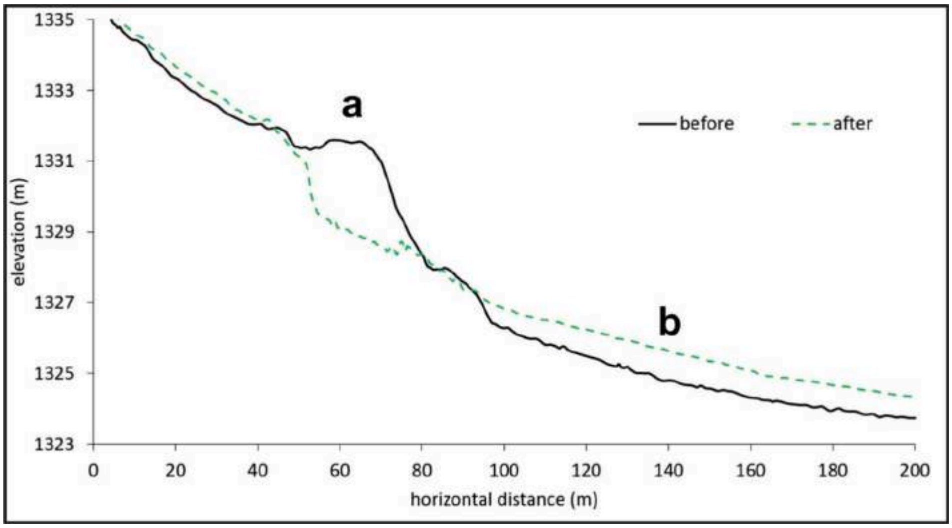

Fig. 6. Profile of gully erosion (a) and deposition (b) in the unpaved road and ditch (see Fig. 4).

Fig. 7. Tiled model textured and contour view of the topography surveyed with SfM-UAV on 15.04.2018.

consolidated materials. However, the Nuria mine changed the physical properties of most of the valley substrata, from consolidated materials (sandstone and limestone) to unconsolidated sandy and clayey mine waste deposits. The comparison of pre-mine and post-mine drainage density are, therefore not directly comparable, as differences in substrata are to be considered.

The change in materials used to restore to a pre-mining condition should be taken into account in rehabilitation designs to adapt the drainage density to observed parameters of a nearby drainage network (analogue) developed on materials similar to the mine wastes (Hannan, 1984). The drainage density of this "reference area", used as a valid input for geomorphic mine rehabilitations in the Alto Tajo, is 110 m ha^{-1} (Zapico et al., 2018). Based on this value and excluding gullies, the post-mine 2010 drainage density was 58% lower than it should have been to ensure long term stability. Although some gully areas were stabilized before 2018 (Zapico et al., 2020), the gully channel length in 2018 persists like that of 2010 because new gullies have formed, mostly in the southeast of the mine, outside the current stable, geomorphically reclaimed areas (Fig. 3).

4.2. Long and short-term gully processes in the Nuria mine

Gully erosion and landslides are the main threats of instability in worldwide active and reclaimed surface mines (Reed and Kite, 2020). In the Nuria case, site drainage system ditches dated 2010 are concentrated at the edges of the mine, leaving many areas with no drainage, thereby leading to the onset of active gullying that alter mine stability and increase sediment yields. The determination of the average gully migration in the main Nuria mine and its acceleration are evident (Fig. 9). Continued gully headcutting may capture the ponds, triggering flash floods, with likely harmful effects downstream to the natural park. Merely 130 m separate the active gully knickpoint and the weakest location in the unconsolidated sand dam of one of the ponds. The sediment yields downstream of the gully are similar to values reported by DoDs in a gully of an open-pit coal mine dump associated with freeze-thaw cycles and meltwater erosion (Gong et al., 2019).

This adverse gullying phenomenon is well-known (Collier et al., 1970) and occurs in the absence of a proper drainage system. Fluvial erosion creates an intruding channel network, leading to sediment yields that risk loading the natural fluvial system (Zapico et al., 2017), and the

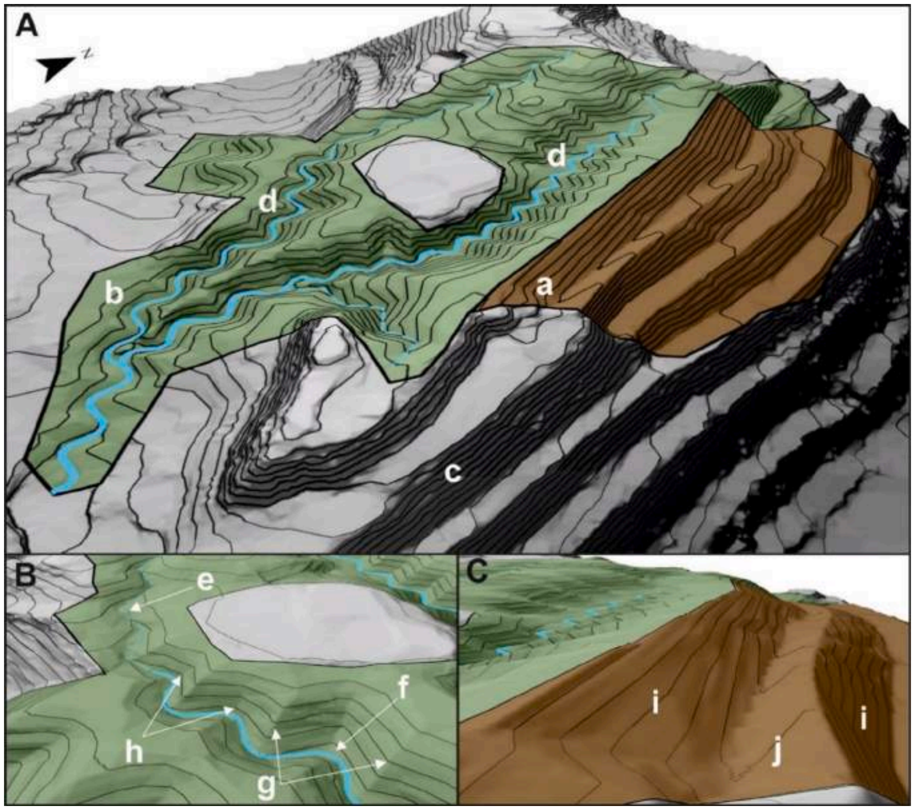

Fig. 8. A series of 3D views of the geomorphic and terrace rehabilitation design for "β2" waste dump in the Nuria mine: general (A) and details (B and C). (a) reclaimed area in terraces; (b) geomorphic rehabilitation; (c) original surrounding topography; (d) main channels with zig-zag (e) and meander (f) patterns; (g) convex-concave sub-ridges; (h) concave swales; (i) outslope; (j) berm with inverted gradient.

Fig. 9. Oblique photo of the main active gully erosion in the Nuria mine threatening an upstream pond (photographed on 26.03.2020). Road (a); left (b1) and right (b2) headcutting gully erosion; earth—sand—dam (c) enclosing the pond (d); highwall (e); weakest area in the earth—sand—dam (f). Photo by DGDRONE (2020).

destruction of sensitive structures such as roads or ponds. Additional evidence of water reproducing natural fluvial processes in the mine is the main gully profile becoming concave (Fig. 6). Gullies can also appear linked to other mining zones, such as the edge of reclaimed filled valleys and downstream of retention cells, as is typical of coal mines of central Appalachia (Reed and Kite, 2020). Our observations demonstrate a rise in the number of gullies with increased drainage area. Gully appearance due to drainage network removal is not exclusive to the mining industry, as it also occurs due to other anthropogenic activities such as urbanization (de Albuquerque et al., 2020), and the combination of both urbanization and agricultural practices (Sofia et al., 2014). Therefore, introduction of functional, long-term and steady-state drainage networks should be incorporated in both mining rehabilitation and other disciplines.

4.3. Restoring a drainage network through geomorphic rehabilitation

Since 2018 a new geomorphic rehabilitation project using GeoFluv methodology is recovering a formerly terraced zone in the Nuria mine. The novelty in this case is that it is a first instance that such a methodology is being adapted to pre-existing terraces. Our design demonstrates how a geomorphic rehabilitation approach can be adapted to traditionally constructed rehabilitation. Using a catchment as the main rehabilitation unit (Hannan, 1984), a new landscape was designed accounting for the often suggested features: appropriate drainage density, channels with concave profiles without knickpoints and bankfull cross sections, and convex-concave hills (Stiller et al., 1980). Other important hydrological principles included in this design are: the constructed drainage density is adapted to the final rehabilitation landscape in terms of sediment type and slope; and, with increase in drainage area, channel length and cross-sections also increase (Hannan, 1984). These features also characterize another geomorphic rehabilitation project undertaken in the Nuria mine in 2017 (Fig. 10, A and B). Here a terraced waste dump experienced severe rill and gully erosion, preventing the support of a new ecosystem. Fig. 10, C-D shows the evolution of the first geomorphic rehabilitation done in the Alto Tajo Natural Park in 2011 (Zapico et al., 2018).

A recent study proposes overcoming the lack of a proper drainage system in slope surfaces with terraces by introducing many straight intercepting drains following the maximum slope, instead of few ditches following the contours and a reinforced concrete lattice (Kou et al., 2020). This approach assimilates two important features of Fluvial Geomorphic Rehabilitation: increase the drainage density and avoid concentrating water and sediment. However, the Kou et al. (2020) system is still based on artificial landforms, which do not ensure long-term stability.

Since a rehabilitation project should be based on the construction of detailed natural shapes adapted to the surrounding area, it requires accurate topographic information (Stiller et al., 1980). We conducted a UAV-SfM survey with a 4.4 cm vertical accuracy (Table 1) as the base of our design. It is lower than that of other topographies surveyed in the area (Zapico et al., 2020, 2018), because the control/check points were measured with a differential GPS instead of a total station, and flight height was larger. This error is present in the final design topography.

Fig. 10. Other geomorphic rehabilitation surfaces in mines of the Alto Tajo: Nuria (before, A; after, B) and Machorro (before, C; after, D; present, E). (*) pond position is used as reference. A and B oblique photos by DGDRONE.

4.4. Next steps to fully stabilize and restore the Nuria mine

The risks of the Nuria mine arose from the lack of a proper closure plan. The terraced waste dumps occupying half of the mine have been or are being stabilized and restored. However, the rest of the mine ("α" in Fig. 1) is experiencing severe erosion by an unstable, interim drainage network, thereby threatening the long-term stability of the mine. Not only is it increasing drainage density, but it is also shaping channels with predominately concave profiles that can affect roads and ponds in the Nuria mine. If erosion reaches a pond, a flash flood may be generated, moving to the two downstream waste dumps, thereby potentially creating a catastrophic massive earth movement. Hence, urgent measures are required to restore the "α" zone.

Since geomorphic rehabilitation is based on introducing a locally adapted channel network, future plans should be based on this preferred methodology. Expert geomorphic designs can reduce erosion by as much by half in comparison to conventional designs (Hancock et al., 2019). Specifically, ponds located at the highwall base should be removed by filling them with waste material and regrading. The final configuration should be similar to the geomorphic rehabilitation in the nearby Machorro mine (Zapico et al., 2018). Furthermore, the area between the ponds and the waste dumps should also be regraded to introduce a drainage network and avoid the present rill and gully erosion. Apart from stabilizing the restored areas, geomorphic rehabilitation also allows better diversity of plant communities compared to traditional rehabilitation, characterized by uniform topography and linear slopes of post-mining sites (Fleisher and Hufford, 2020). The average gentle slope of the design will also optimize soils moisture availability, improving the development of vegetation (Vidal-Macua et al., 2020).

Unacceptable environmental practices and an inadequate closure plan involved the rejection of a new concession extension in the Nuria mine; authorities did not return the bond release to the mining owners. This guarantee was confined to meet expenses to stabilize the rotational landslide. The current rehabilitation occurring in another waste dump is being carried out by the only active mining company in the area, by jointly planning with the mining administration and the natural park authorities an attempt to gain stability of the entire mine through several compensatory mitigation measures. This agreement enables the mining company to access a place to stockpile part of its wastes with the commitment to regrade the final topography with geomorphic rehabilitation, thereby removing stability risks. Owing to the high cost of earth movement and completion of bond release, this type of collaboration between authorities and the local active mining company may be extended to stabilize and restore the rest of the mine.

4.5. The false dilemma between a geomorphic (natural drainage recovery) or soil focus in mine rehabilitation

The use of a geomorphic landform design approach in mine rehabilitation with respect to soils - either by using soil erosion modelling, or protocols for handling the soil - also in mine rehabilitation is still often raised as a disjunctive question. One must often choose between two supposedly mutually exclusive options – either use fluvial geomorphic landform design with a natural drainage recovery, or else use soil erosion modelling, thereby improving physico-chemical properties. However, this is a false dilemma, since both approaches are required and are complementary. Several studies have demonstrated that joint use of geomorphic landform design and landscape evolution modeling provide complementary capabilities to enhance mine rehabilitation (e.g., Hancock et al., 2019). The cause of this false dilemma appears to lie in the understanding that both elements (drainage network and soils) operate at different scales. The drainage basin operates at a landscape scale, whereas soil operates at the catena, hillslope scale; both are compatible. As demonstrated by the Nuria example, a specific drainage density is needed to naturally drain that landscape, independent of soil treatment.

This reasoning goes beyond: we argue that without a geomorphic approach of reconstructing drainage systems equivalent to natural ones in order to repair land and ecosystems disturbed by mining, recovery will remain partial, and should not be termed either 'ecologic' or 'landscape' rehabilitation. Avoiding soil erosion is indeed a condition, and key issue, to mine rehabilitation (Vidal-Macua et al., 2020). But this is insufficient, nor is it currently the best possible practice. The reasons for this insufficiency are listed hereafter: (a) most functional ecologic processes occur on the Earth's land surface at a watershed scale, driven by hillslope runoff and fluvial processes: (b) visual blending of waste dumps with the surrounding is nowadays a major issue for society. Merely avoiding erosion is no longer sufficient for most government agencies, local inhabitants and visitors to a mine.

5. Conclusions

A very defective mining operation and the lack of a proper closure plan in the Nuria mine are threatening one of the most biodiverse natural parks in Spain, the Alto Tajo. As a consequence of the mining activity the original drainage network was considerably reduced and the new pit configuration, with three ponds filling topographic depressions, modified the original catchments forming two new endorheic subcatchments. One of these ponds is enclosed by an unconsolidated dam and it is threatened by a rapidly advancing gully, which was created by the redevelopment of the obliterated drainage network. This lack of a locally congruous drainage system is being overcome through the application of a Fluvial Geomorphic Rehabilitation approach, creating a new, dynamically equilibrated landscape. This is organized in a main catchment and sub-catchments with a drainage density adapted to the materials and slopes of the rehabilitated area, and with natural features such as concave channels and convex-concave hills adapted to preexisting terraces. The current Nuria mine rehabilitation is a good example of the compensatory measures between other active mining companies and local authorities, which can be explored to apply corrective action to adequately rehabilitate abandoned mine sites.

As a global contribution, we provide here an example of mine rehabilitation demonstrating that, with a (geomorphic) focus on reestablishing drainage systems equivalent to natural ones, mine rehabilitation: (a) is stable; (b) natural recovery can be complete, and should either be termed 'ecologic' or 'landscape' rehabilitation.

CRediT authorship contribution statement

Ignacio Zapico: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Jonathan B. Laronne:** Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Lázaro Sánchez Castillo:** Validation, Writing - review & editing, Funding acquisition. **José F. Martín Duque:** Conceptualization, Methodology, Validation, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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