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A Somolinos quarry land stewardship history: From ancient and recent land degradation to sensitive geomorphic-ecological restoration and its monitoring

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ABSTRACT

This research documents the successful application of a novel holistic approach to return land degraded over thousands of years of use to full ecological function. The surroundings of the Somolinos hamlet in Central Spain illustrate a millennial history of land transformation and degradation by agrarian and extractive activities exacerbated at the second half of the 20th century by mechanized mining. This land stewardship history was culminated by a recent intervention of geomorphic-based ecological restoration and its monitoring.

Historic anthropogenic processes which triggered gully erosion were intense deforestation for agriculture and grazing, and construction materials quarrying. From 1963 to 2006 mechanized quarrying operated over ancient extractive landforms. In 2007, a conventional rehabilitation mitigated risks but failed at controlling erosion and promoting soil and vegetation reestablishment. A geomorphic-based ecological restoration was accomplished since 2011. The GeoFluv-Natural Regrade CAD software was used for geomorphic landform design, and construction was completed with a carbonatic colluvium topdressing supplemented with a manure-amended soil, that was seeded with grasses. The whole process was a truly complete application of ecological engineering.

One of the main purposes of this research was to carefully scrutinize the completed project, to evaluate its effectiveness and, if any deficiencies were found, to analyze their causes, so that they could be avoided in the future. Therefore, the landscape evolution and erosional behaviour of the restored area has been monitored from 2011 to 2020 through a time-lapse sequence of several oblique aerial photos, and by comparing topographies through Digital Elevation Models (DEMs) of Difference (DoDs). Those topographies were surveyed with differential GPS (DGPS) and with Structure from Motion (SfM) combined with Unmanned Aerial Vehicles (UAVs). This monitoring revealed: (a) landscape healing and diversification of the vegetation community composition and structure, as a result of the environmental heterogeneity of the geomorphic design; and (b) absence of hillslope and channel erosion for 99.8% of the area with limited surface erosion zones in 0.2% of the restored area.

Our analysis attributed those limited erosion zones to a combination of: (a) minor design oversights; (b) slight construction deviation from the design grade; and (c) excessive runoff entering the repaired area that exceeded the design discharge. These erosion zones started to stabilize five years after initial restoration and achieved steady-state stability at nine years.

The main lesson learnt from these minor deficiencies is that such erosion zones can be avoided at the design phase within GeoFluv-Natural Regrade by checking proper convex-concave slopes and concave channel profiles and by carefully considering any adjacent runoff entering the designed areas, which influence the channel's tractive forces. The use of Landscape Evolution Models, such as SIBERIA, can also identify design anomalies subject to erosion. Then, after rigorously inspecting the design, it is imperative that the construction is completed true to the design by defining and following construction tolerances.

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1. Introduction

This paper deals with land degradation and healing by humans. Its content is structured according to the main motivations of the research, which are: (a) to draw the attention on how, in large areas of Planet Earth such as the Mediterranean Basin, the history of land transformation and degradation is very long, having imprinted not only ecological effects, but unequivocal geomorphic footprints, somehow neglected in the scientific literature; (b) to demonstrate, through a real case, how we humans have now very advanced knowledge and tools (geomorphic-based ecological restoration) for properly healing ecosystems in which the damage has affected or destroyed the foundations of the life-support (landforms); (c) to answer a specific research question on how these new geomorphic-based land restorations behave through time, by monitoring nine years of evolution of the recovered scenario, trying to understand any deviation. All this is referred to a specific site: the Somolinos quarry, in Central Spain.

We humans were born modifying the environment and moving earth to make life easier, and to improve our chances of survival. Hooke and Martín Duque (2020) provide a detailed description and some quantifications of such history, focusing in the dramatic increase of human earth moving in the last decades. Human biogeomorphic work is not conceptually different from that of many other organisms that alter Earth's surface to suit their own convenience and comfort (Butler, 1995). But the cumulative geomorphic effect of the human activity has produced a distinctive assemblage of landforms and landscapes. Thus, in many places, much of the small-scale topography that we see today is a consequence, either directly or indirectly, of human endeavour. An example is gullying and soil erosion initiated by land clearance (Dotterweich, 2013). In most cases, such land transformation involved land degradation. However, we humans have also learnt how to restore ecosystems exhausted through millennia. The current and urgent need for restoring these degraded lands is clear (UNEP, 2019).

In ecological restoration, the goal is not to simply restore the physical elements of the ecosystem (*e.g.*, trees), but primarily the ecosystem functionality. This is a complex process when the surficial geology is highly disturbed, as in the example we report here. The 'conventional approach' to land restoration degraded by earth movements commonly fails, because the new topographies tends to be linear, with slopes of constant gradient or with terraces and unnaturally rigid drainage structures. Such landforms do not restore natural functions, and they are not stable over the long term. Without constant costly maintenance, most of them gradually evolve to resemble complex natural landforms (Haigh, 1985; Sawatsky and Beersing, 2014). Geomorphic restoration, still a young discipline, is a solution that helps solving these problems. During geomorphic restoration, the landscape is designed and shaped to mimic both the look and —most importantly— the functionality of nature (Toy and Chuse, 2005; OSMRE, 2019). This provides the foundation on which, after proper soil and vegetation restoration, the ecosystem goods and services of our life-support systems can be firmly re-established. On landforms mirroring stable natural ones, soil erosion is minimized, so conservation of nutrients released by decomposition, cycling of organic matter, and nitrogen fixing by microorganisms are maximized. Minimizing soil erosion promotes vegetation succession (Moreno De Las Heras et al., 2008). These are key functions needed to restore the natural capital on derelict and degraded lands (Bradshaw and Chadwick, 1980).

There are several methods of geomorphic restoration (see Hancock et al., 2020), used mostly in mining. They seek to replicate the relief and surficial architecture of stable natural landforms that are well-suited to the geologic and geomorphic conditions of the site, taking into consideration the future local climate and possible changes in land use. The goal is to re-establish a rough dynamic equilibrium between landforms and processes, leaving the 'fine-tuning' to natural processes (Schumm and Rea, 1995; Toy and Black, 2000; Toy and Chuse, 2005). Geomorphic restoration of mining sites in the United States is guided by the pioneering US 1977 Surface Mining Control and Reclamation Act (SMCRA, 1977), further developed by Stiller et al. (1980), Toy and Hadley (1987) or Bugosh (2000, 2003), among others. Backfilling and regrading is designed to blend the restored mined areas to complement the drainage pattern of the surrounding terrain. One of the most successful built examples is that of the La Plata open pit coal mine in New Mexico (Bugosh and Epp, 2019). Geomorphic mine restoration is applied in Canada (Sawatsky and Beckstead, 1996; Sawatsky and Beersing, 2014) and Australia too (Waygood, 2014; Kelder et al., 2016). Spain has already notable examples (Martín Duque et al., 2010, 2020; Zapico et al., 2018, 2020), after pioneering developments in this field (Martín Duque et al., 1998; Nicolau, 2003).

Healing degraded ecosystems based in geomorphic restoration is still a new discipline Therefore, there is a clear need for assessing and monitoring results, to cover the significant gaps in knowledge that we still have. One of such knowledge gaps refers to the key indicator of quantifying erosion, identifying the causes when it occurs, since high erosion is an indicator of ecosystem recovery failure and instability (Gong et al., 2019; Hancock et al., 2019; Martín-Moreno et al., 2016, 2018). Erosion removes soil, moisture, nutrients, and seeds offsite, thus inhibiting soil-forming processes and plant re-colonization (Moreno De Las Heras et al., 2008). Soil erosion can be measured in the field through sediment ponds or dams (Zapico et al., 2018; Bugosh and Epp, 2019), or through multi-temporal topographic analysis (Zapico et al., 2018; Gong et al., 2019; Xiang et al., 2019). The latter consists of comparing consecutive topographies through Digital Elevation Models (DEMs) of Difference (DoDs) (Williams, 2012). Those topographies can be surveyed with a wide range of instruments or methods: differential GPS (DGPS), Total Station (TS), Terrestrial Laser Scanning (TLS), Aerial Laser Scanning (ALS), or the emerging technique of Structure from Motion (SfM) combined with Unmanned Aerial Vehicles (UAVs). SfM-UAV is replacing the rest due to its ease of use, lower cost, and high accuracy and resolution (Carrivick et al., 2016). The use of DoDs for monitoring erosion in geomorphic-based ecological restoration is still very scarce, but it is a trend and new perspective. This circumstance reinforces the opportunity of this article.

From the described background, the motivation and aim of this paper is analysing a long history of land transformation and land healing near a small hamlet (Somolinos) in central Spain, covering the three main referred purposes: historic land transformation, geomorphic-based ecological restoration, and erosion monitoring. During more than two millennium, surrounding deforestation, mining and quarrying triggered gully erosion. From 1963 to 2006, mechanized mining superimposed severe transformation on formerly ruined landforms. In 2007, risk mitigation measures were adopted. Finally, in 2011, proper land healing started to reverse the degradation process, through geomorphic-based ecological restoration. From 2011 to 2020, such restoration has been monitored in terms of landscape and erosion evolution to confirm land healing.

Although this is a local example, we maintain these conclusions are solid and provide global application, since: (a) although this is a Mediterranean landscape, which biome covers only 2.43% of Planet Earth (Wade et al., 2003), the same fluvial and slope geomorphic processes that are active here are dominant over the majority of planet Earth landmass, where during the last 10.000 years, practically all of its continental and inland surfaces (outside small areas such as sea sands and cold deserts) are being shaped by such processes; (b) the handled earth materials (sand and clay) are very common all over the world; (c) the evolution of the restored area spans over nine years of adaptation.

Increased energy production from renewable sources—solar, wind…—are popular approaches to mitigating climate warming, but this change will be accompanied by significant increases of mining in sensitive landscapes, since the metals and rare earths needed for these systems commonly lie in areas that overlap with protected areas and biodiversity hot spots all over planet Earth (Sonter et al., 2020). Therefore, we argue that the proper use of geomorphic-based ecological restoration will be a key issue in the decades to come.

2. Regional setting and characteristics of the area to be reconstructed

2.1. Physical environment

The Somolinos quarry was situated at the North of the Guadalajara Province, in the vicinity of the small hamlet of Somolinos (1240 m.a.s.l.), 120 km north of the city of Guadalajara and 170 km northwest of Madrid (Fig. 1).

The physiographic setting of the area is a high plateau (called *Sierra de Pela*) located where the two main mountainous systems of the interior of the Iberian Peninsula join: the Central System (an uplift of Palaeozoic and Pre-Palaeozoic crystalline basement) and the Iberian Range (an uplift of Mesozoic —Upper Cretaceous— sedimentary rocks). This high plateau is also the main divide between the Tagus and Douro drainage basins in this region.

The derelict quarry was placed at the south footslope of a residual platform (mesa) of the high plateau (see Fig. 1), culminated at a height of 1450 m.a.s.l. Marine limestones and dolostones form the caprock and mid-upper slope (shoulder) of this mesa. Fluvial sediments of the Utrillas Formation (clayey and gravelly silica sand, which were the extracted minerals) form its backslope, footslope and toeslope (Fig. 2B). Where mid-lower slopes have not been modified by mining activities, a carbonate colluvium comprised of reworked caprock sediments drapes the Utrillas Formation. Rendzic leptosols have developed on the consolidated limestones and dolostones of the mesa platform and colluvial regosols typify the carbonate colluvium covering the clayey and sandy formations.

The main natural feature of the area is the Somolinos mountain tufa lake (Fig. 1), where an analysis of its sedimentary record allowed interpreting climate change and human impact in central Spain during Roman times (Currás et al., 2012).

The climate and vegetation of the area have been summarized by Currás et al. (2012, p.32). The region has an unusually cold Mediterranean climate, with a mean annual temperature of 11.8 °C (for Atienza, 15 km east of Somolinos, at 1169 m.a.s.l.), characterized by long and cold winters. January is the coldest month, with mean temperatures of 2.6 °C, and July is the warmest month, with mean temperature of 21 °C. Mean annual precipitation is close to 600 mm, most of which falls during winter months. The vegetation is characterized by calcicole open evergreen forests of *Quercus rotundifolia* with *Juniperus oxycedrus*, *J. thuriferae*, *J. hemisphaerica* and *Q. faginea*. The degradation of these woodlands leads to the expansion of open shrub communities dominated by *Genista scorpius*, *Lavandula latifolia*, *Thymus vulgaris*, *Linum suffruticosum* and *Helianthemum rotundifolium*.

The high ecological and landscape value of this area is reflected by its recognition as a Site of Community Importance (SCI)—*Sierra de Pela*, code ES4240007 within the European Natura 2000 Framework. Additionally, the quarry is located at the edge of two protected areas: The Natural Monument *Sierra de Pela y Laguna de Somolinos* and the *Sierra Norte* Natural Park. The latter is also both a Site of Community Importance (SCI) and a Special Protection Area (SPAs)—*Sierra de Ayllón*, code ES0000164 within Natura 2000 (CLM, 2020). These circumstances highlight the importance of the quarry's conclusive ecological restoration.

2.2. History of land transformation of the Somolinos quarry

As most of southern Europe, the Somolinos region has been subject to an intense transformation by humans. Currás et al. (2012, p. 32-33) offer a detailed history of human occupation of the Somolinos surroundings from the Neolithic, providing proofs and references of human activities in the area from the Bronze Age, Iron Age (Celtiberian culture), and subsequent Roman, Visigothic, Islamic and Christian occupations, with evidences of relatively high population densities since the 8th century. Although we do not have unequivocal facts, it is probable that soil erosion and gullying were initiated here very early after human occupation by two anthropogenic processes of land clearance (by intense deforestation for agriculture and grazing) and by earth movements associated with extractions of sand, clay and limestone ashlars, likely to enable construction of the near Somolinos hamlet (Fig. 2A and B). Evidences of gully erosion triggered by anthropogenic land disturbances have been provided for nearby regions with similar physiographic settings and comparable human occupation (Martín-Moreno et al., 2014).

In 1963, the first mechanized Somolinos quarry was opened very near the hamlet, on a densely gullied slope (Fig. 2A), and was closed in

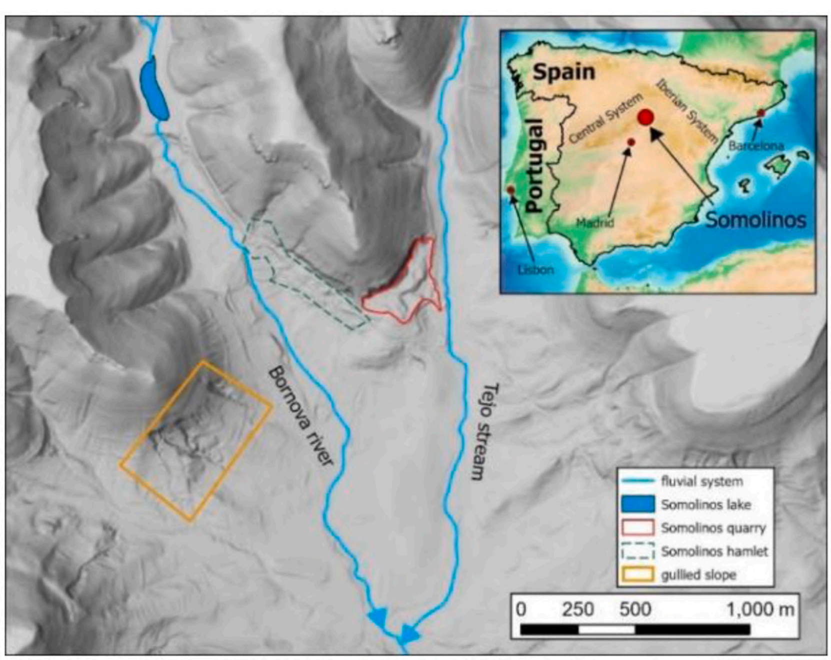

Fig. 1. Location of the Somolinos quarry in central Spain, at the edge of the Somolinos hamlet.

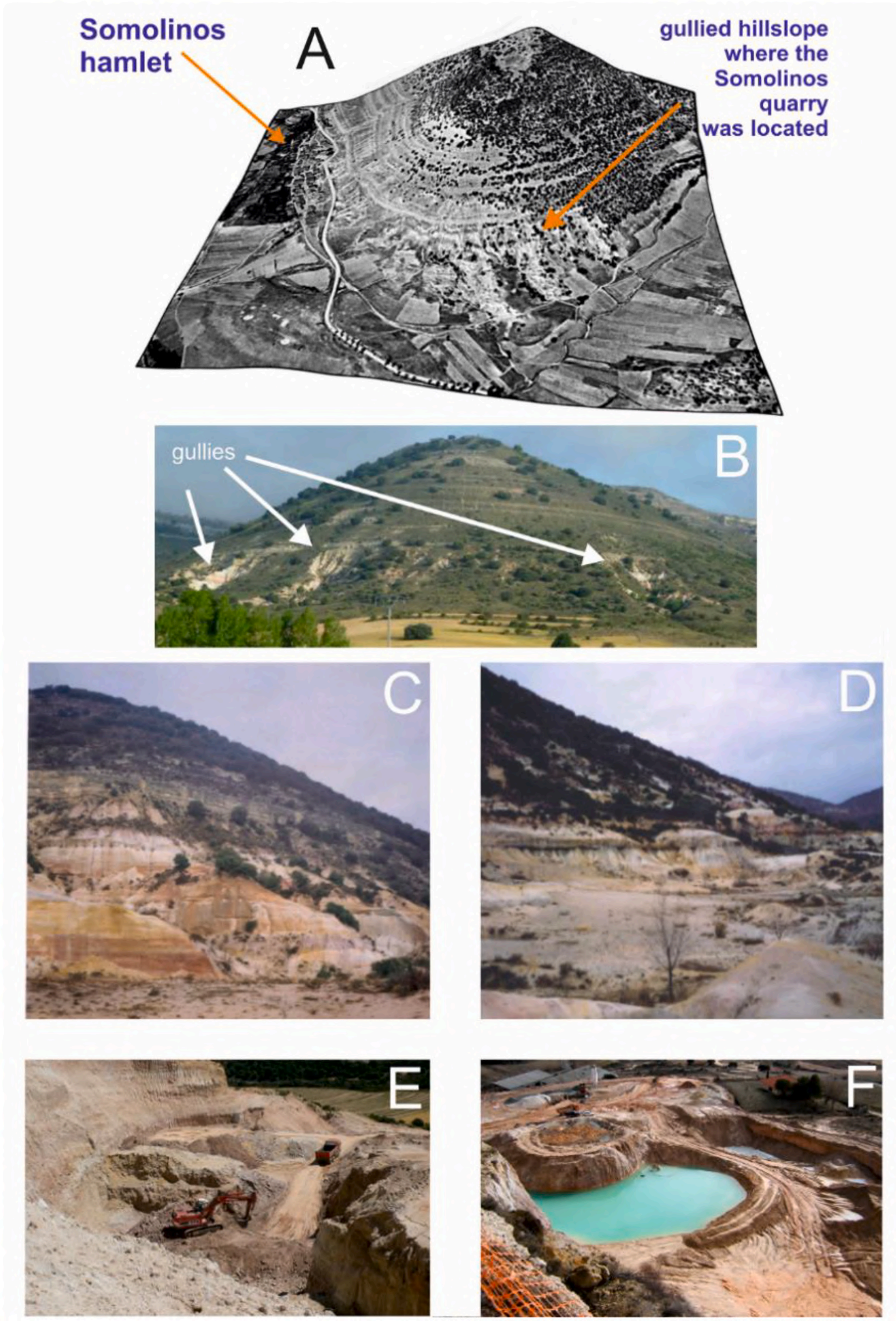

Fig. 2. (A) 3D view obtained from the overlay of a DEM and an aerial photo of 1956 (source Spanish Geographical Institute, https://www.ign.es/web/ign/portal). (B) Current photography of the mesa landform located southwest of the Somolinos hamlet (see Fig. 1, gullied slope, for its location). This image is provided to illustrate a location-for-time-substitution, since this must have been the landscape existing around the Somolinos hamlet before the mechanized quarrying. (C y D) Photos taken in 1996, after the exploitation that began in 1963 (photos from the archive of the Mining Service of Guadalajara). (E y F) Photos taken during the 1998–2006 exploitation.

1984. The extracted (silica) sands and clay were used to manufacture refractory bricks and segments to cover national and international metal melting furnaces. Fig. 2C and D show photos taken in 1996, after this exploitation. From 1998 to 2006, another company continued quarrying sand and clay, this time for the construction industry. Fig. 2E and F show photos of this period.

2.3. Conventional rehabilitation (2007–2011)

The conventional rehabilitation of the Somolinos quarry was performed in 2007 with a low budget of the bond guarantee. The action was a basic risk reduction approach consisting of broad stepped platforms linked by short rectilinear slopes. Different ponds within the platforms acted as sediment traps. No topsoil could be applied upon the regraded surfaces, leaving the loose sands exposed followed by tree and shrub plantings, intended to control erosion. By 2011 the platforms and the rectilinear slopes showed severe erosion, the pools presented signs of accelerated filling by sediments, and the planted vegetation was totally ineffective at controlling erosion (see Fig. 3). The most positive outcome was the pools acted as sediment traps. However, the erosion from the rest of the surface was sporadically released to the surroundings as suspended sediment, impacting the downstream fluvial network (Fig. 4).

3. Geomorphic-based ecological restoration

3.1. Methods

3.1.1. Design

The GeoFluv-Natural Regrade method was used to design the new topography of the former Somolinos quarry. GeoFluv is a fluvial geomorphic method for land restoration, to design landforms similar to those that naturally would 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. Natural Regrade is the software that aids users to make and evaluate GeoFluv designs in a Computer Aided Design (CAD) format, from the input values. GeoFluv first gained respect after its successful use in coal mines of New Mexico starting in 1999 (Bugosh, 2000). The GeoFluv method allows designing landforms that will function as mature 'natural' ones at the completion of restoration grading. 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 (Zapico et al., 2018; Bugosh and Epp, 2019; Martín Duque et al., 2020).

Since mine and quarry wastes are usually unconsolidated materials, alluvial or colluvial analogues are often used as landscape reference areas for design inputs. For the Somolinos scenario, colluvial channels

Fig. 3. The 2007 image shows the quarry closure and stabilization works, regrading platforms and sediment ponds construction (the black arrow points to the main one, which is the one visible at Fig. 2F). As it can be seen in the 2011 image, four years later, the surface had not recovered any soils or vegetation. Photos by Paisajes Españoles.

Fig. 4. Left, suspended sediment releases from the Somolinos quarry to the fluvial system. Center, confluence of the Tejo stream with the Bornova River. Right, high turbidity at the Bornova River. See Fig. 1 for locations. Photos by local Environmental Rangers, as of February 23, 2007.

and related hillslopes were identified and measured, near the Atienza town. The earth materials at this place are similar to those of the restoration site, and they are located under very similar climatic conditions (Atienza is 15 km east of Somolinos). At that position, this landscape had adjusted over time to convey water runoff over land without high erosion rates. It is important to note that this goal of 'stability' does not mean nil erosion, but the minimal rates present on local natural land that is not considered to have problematic erosion. Using such inputs to design restoration landforms approaches a stability performance comparable to the 'stable' reference area landforms. Examples of such input measurements are drainage density and maximum distance from ridge to channel head or sinuosity indexes. Precipitation values of Average Recurrence Intervals (ARI) that relate to the bankfull and flood-prone discharges are also used, as are hydrologic values such as the maximum stream velocity associated with bankfull discharges in the local reference areas (Rosgen, 1994, 1996). In addition to these field inputs and ARI events, a CAD model of the site with its topographic information is needed. Finally, the design area is set, as well as a local base level – the point where all runoff will leave the restoration project area, connecting to a similar altitude and slope angle, therefore limiting the erosion potential.

The existing spoils at the quarry, regraded into broad platforms and ponds at the 2007 risk-mitigation intervention (see Fig. 3), were the only materials that could be cost-effectively used to accomplish the described geomorphic design. The construction had to be conducted without importing or exporting materials. These spoils were dominantly sand and clay. The geomorphic-based ecological restoration plan had to be complemented with subsequent specific measurements about replacement of soils and re-vegetation. For topsoil dressing, the only available material at the surroundings of the quarry was the carbonatic colluvium which draped the extracted mined material, and was chaotically disposed at the edge of the derelict area; no true soil was present. Carbonatic colluvium has been successfully used as subsoil restoring similar scenarios (Martín Duque et al., 1998, 2010). The spreading of this carbonatic colluvium on the geomorphically regraded mine spoils would replicate the surficial deposits of the original (natural) slopes, and it has therefore a sound ecological basis. Chemical analysis of the colluvium would reveal the need or not of organic amendments. The main aim of the selection of the plant species to be used in the revegetation process was protecting the soil against erosion.

3.1.2. Execution

The designed landforms were staked out for guidance using a Leica 1200 DGPS. The earthworks machinery selected were an excavator, a D6 bulldozer and two tipper trucks. A specific earth-movement plan was laid out, according to topographic conditions, internal roads and operational cycles. Manual manure spread, seeding and soil rake (to cover the seeds) were carried out.

3.1.3. Landscape evolution and erosion monitoring

The restored Somolinos quarry landscape evolution has been monitored from 2011 to 2020 through a time-lapse sequence of several oblique aerial photos, obtained both from aviation and drone photographs. The erosion monitoring has been performed by comparing consecutive topographies through DoDs (Williams, 2012). For that, public topographic sources have been used: (a) 1:50,000 topographic map with 20-m equidistant contour of the year 1955 (IGN, 1961) and 1:25,000 topographic map with 10-m equidistant contour (IGN, 1995) and; (b) high resolution LiDAR data surveyed by ALS in 2010 and 2019, provided by the Spanish National Plan for Aerial Orthophotography (Table 1).

In addition, site-specific topographic surveys were conducted in 2011, 2012, 2015 and 2020 (Table 1). In 2011 and 2012, the area was surveyed with a Leica 1200 DGPS. In 2015 and 2020, SfM-UAV surveys were carried out for the entire restored area. The 2015 SfM-UAV survey was performed with 350 zenithal angle photographs by a DJI Phantom 3 Pro at a constant altitude and with a 50-m above ground maximum height. The Ground Sampling Distance (GSD) was 1.9 cm pix^{-1}. 15 targets were placed along the restored area to be used as control points. The targets were measured with a DGPS. Photographs and control points were processed with the Agisoft Metashape Professional 1.6.2 software, to obtain a dense point cloud and an orthophoto. The main parameters used in this software were: alignment accuracy, *highest*; key point limit, *100.00;* tie point limit, *0;* dense point cloud quality, *ultra-high;* filter mode, *aggressive*. The final pixel error was 0.7. The 2020 SfM-UAV survey was completed following the same procedure except that: (a) a DJI Phantom 4 Pro was used; and (b) in addition to zenithal pictures (450), oblique ones (207) were taken. In this case, the GSD was 1.3 cm pix^{-1} and the final pixel error was 0.2. 16 targets were used as control points and eight as check points. Again, all of them were measured with a DGPS. The final vertical accuracy obtained from the check points was 6 cm, which was also assumed for the 2015 survey. Both dense point clouds were cleaned to remove non-ground elements such as vegetation or noise by using the LP360 Advanced edition software (Qcoherent software LLC, 2015). Each topography was transformed to a DEM.

Based on their accuracies, comparisons were conducted using the Geomorphic Change Detection methodology and software (Wheaton et al., 2009; GCD, 2018), assuming a confidence level of 95%. This procedure has been widely used, including mines (Cucchiaro et al., 2018; Williams, 2012; Williams et al., 2020; Xiang et al., 2018; Zapico et al., 2020). The topographic maps, the 2010-LiDAR-ALS and the 2015-SfM-UAV were used to estimate the total earth movement related with mining activity and geomorphic restoration. The topographies surveyed with DGPS, the 2019-LiDAR-ALS and the two SfM-UAV surveys were used to know the erosion and sedimentation occurred at the area restored in 2011.

Table 1
Topographic data and related accuracy used for the erosion monitoring of the Somolinos quarry.

Date	Source/method	Nº photos	Point cloud density	RMSE check points		
				Nº of check points	x,y	z
		#	pts m^{-2}	#	m	
1955-1995[a]	50,000 and 25,000 topographic maps with 20-m and 10-m equidistant contours respectively	n.a.	n.a.	n.a.	n.a.	5.6[b]
29.01.2010	LiDAR-ALS	n.a.	0.5	n.a.[c]	0.3[c]	0.2[c]
28.06.2011	DGPS	n.a.	> 0.5	n.a.	0.03[d]	0.03[d]
26.03.2012	DGPS	n.a.	> 0.5	n.a.	0.03[d]	0.03[d]
11.12.2015	SfM-UAV	350	2780	n.a.	0.09[e]	0.06[e]
01.10.2019	LiDAR-ALS	n.a.	1	n.a.[c]	0.3[c]	0.15[c]
17.05.2020	SfM-UAV	657	351	8	0.09	0.06

n.a. – non applicable.
[a] This topography represents the previous surface to mining activity. It was reconstructed by using maps where the quarry did not exist (1955) or where its influence in the landforms, due to the quarry magnitude, was slightly noticed (1995), previous to a more profound transformation at the 1998–2006 exploitation.
[b] Derived from a direct comparison with 2010 topographic data of areas without topographic changes between the two dates.
[c] Technical specification (PNOA, 2009, 2019).
[d] Local accuracy could not been obtained for the points surveyed with the DGPS. We assume that these values are similar to those reported in the literature for a similar device (Cucchiaro et al., 2018; Lucieer et al., 2014).
[e] We assume the same accuracy than for the 2020 SfM-UAV survey, since the same field procedure was used.

4. Results

4.1. Design

The initial 3D surface CAD model was obtained by traditional photogrammetry, with photos taken by a piloted light aircraft. Table 2 shows the specific GeoFluv design inputs that were used, gathered at the Atienza reference area. From those inputs, we designed the 'A' to 'Aa+' and 'Cb' type channels of the Rosgen (1994, 1996) fluvial morphological classification. 'A' to 'Aa+' channels have a zig-zag pattern resulting from them flowing around ridges eroded into their valleys' walls. They develop on gradients above 4%. The GeoFluv method associates these greater than 4% channels with this characteristic zig-zag pattern rather than the sinuous meander bends present in the lower gradient 'Cb' channel type. We fitted such fluvial channels and related scalloped hillslopes to the local hydrological, topographic and volumetric conditions of the Somolinos quarry. The number of potential designs is always uncountable. Suitable ones were those which fulfilled the conditions to stabilize erosion and met the earth material volume (neutral balance in this case). Once the optimum alternative was set, the restoration plan was laid out. Fig. 5 shows a 3D view of such design.

Table 2
GeoFluv design inputs for the Somolinos quarry.

Inputs / settings	Method	Value / units
Maximum distance from ridgeline to channel's head	Field work, measuring tape	30 m
Slope at the mouth of the main valley bottom channel (measured at the connection of the channel that drains the quarry with the Tejo stream, see Fig. 1)	Field work, compass	- 1%
'A' channel reach - type of channel with slope higher than 4%, according to Rosgen (1994, 1996)	Field work, measuring tape	12.6 m
Target drainage density	Aerial photo-interpretation and GIS	80 m ha^{-1}
Angle from subridge to channel's perpendicular, upstream (degrees)	Aerial photo-interpretation and GIS	22°
Sinuosity of channels with slope higher than 4% (ratio of channel length to the length of the 'A' channel belt axis)	Aerial photo-interpretation and GIS	1.15
2-yr, 1-h precipitation	Intensity-Duration-Frequency, IDF, curves, Molina de Aragón (#3013) weather station	2.15 cm
50-yr, 6-h precipitation	Intensity-Duration-Frequency, IDF, curves, Molina de Aragón (#3013) weather station	8.92 cm
Runoff coefficient	Assigned according our own experience in similar restored landscapes	0.3

A volumetric analysis of the available colluvium returned a 20-cm depth capacity to cover the entire regraded area. Physical analysis of the carbonatic colluvium showed a dominant loamy texture, considered to be ideal for edaphic development. Chemical analysis yielded the following key characteristics: strong effervescence reaction with hydrochloric acid, pH of 8.45, and EC of 206.9 ± 8.2 μS cm^{-1}. This colluvium had a poor chemical fertility, a very low organic matter content (<0.06 ± 0.02%) and a remarkably low total nitrogen content (0.30 ± 0.12 mg kg^{-1}), which represents a limitation for the establishment of vegetation and a key point to be addressed by the soil amendment. Therefore, the application of local sheep manure, at a dose of 100 t ha^{-1} was selected. This manure also has the potential to disperse seeds from a wide variety of local plant types. The manure placement plan included the whole surface, outside of a central zone selected to evaluate site evolution without manure.

For revegetation, a mix of grass and leguminous herbaceous species was seeded. The species composition were: *Festuca arundinacea, Agropyrum cristatum, Agropyrum desertorum, Lolium westerwoldicum, Vicia sativa, Onobrychis viciifolia, Medicago sativa* and *Melilotus officinalis.* An additional objective was to promote the ecological succession towards the establishment of a forest community (*Quercus ilex* forest). To do so, *Genista scorpius* and *Retama sphaerocarpa* shrubs were introduced by seeds since they facilitate *Quercus ilex* recruitment. Other species were incorporated in order to improve the structure of the plant community: *Dorycnium pentaphyllum, Moricandia arvensis, Piptatherum milliaceum, Lavandula latifolia* and *Colutea arborescens.* The applied seeds dose was of 330 kg ha^{-1}. From a homogeneous treatment of this seeding mixture for the whole surface, divergence in community composition and structure among habitats was expected to be ruled by the environmental heterogeneity provided by the geomorphic design. Thus, three geomorphic-based types of habitats were expected to develop spontaneously through time: *habitat 1*, associated to riparian areas above the channel's

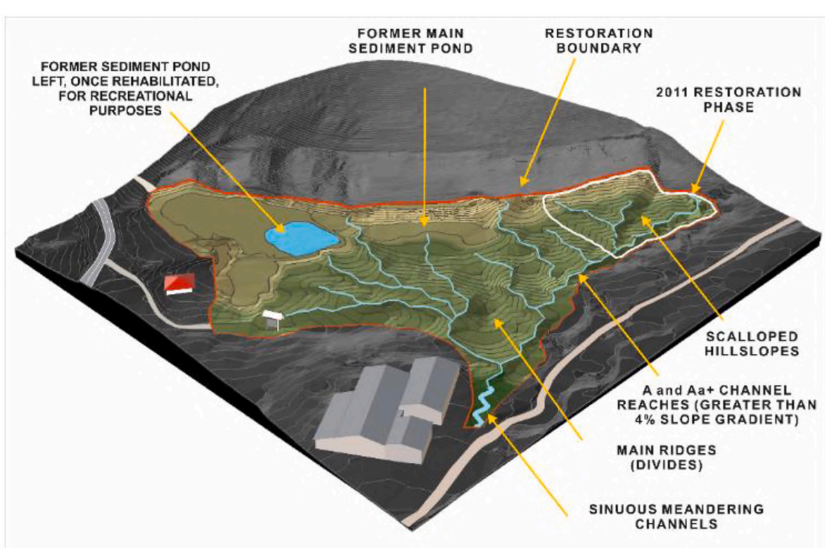

Fig. 5. 3D view of the geomorphic design of the Somolinos quarry. Note the position of the former main sediment pond for specific discussions on it (visible at Figs. 2F and 3).

bankfull stage; *habitat 2,* associated to sub-watershed swales; and *habitat 3,* associated to the rolling uplands between the whole drainage network. In this last case, fertilized and non-fertilized soils would be different ecological environments.

4.1.1. Execution

The planned restoration was executed in two phases, following the budget availability by the funding administration. The respective earth movements were carried out during June of 2011 (one hectare) and October of 2013 (five hectares), with subsequent soil and revegetation works. Fig. 6 shows a set of images compiling all the execution phases of the restoration. The design could not be totally completed at the former main sediment pond (see Fig. 5), due to water saturation of its sediments. The restoration of this persistently wet area was updated as a wetland habitat, although drained from a certain elevation to avoid mudflow risks.

4.1.2. Landscape evolution and erosion monitoring

Fig. 7 is a time-lapse sequence of several oblique aerial photos of the Somolinos quarry, showing its visual landscape evolution.

Fig. 8 shows the result of nine years of vegetation cover development from the designated seed mix. Field surveys confirmed the hypothesized organization of habitat 1 *(Salix spp., Fraxinus spp., …)* developed on fluvial bottom channels; habitat 2 *(Rubus spp., Rosa spp., Crataegus spp.,* …) established at sub-watershed swales; and habitat 3 *(Genista spp., Thymus spp., Santolina ssp., Lavandula spp…)* associated to the rolling uplands (ridges and subridges). In this case, plant cover was higher on manure-fertilized surfaces, where *Agropyrun sp.*, *Medicago sativa* and *Onobrychis viciifolia* were dominant. However spontaneous colonization was less active than in non-fertilized zones, because of the well-known competitive process of seeded and spontaneous plants in reclaimed-mining ecosystems (Vidal-Macua et al., 2020).

Fig. 9 shows the 3D view of the point clouds of the SfM-UAV surveys (2015 and 2020). Table 3 gathers the topographic changes in the Somolinos quarry through time, enabling quantifying human earth movements related with the mining activity and geomorphic restoration process, and the identification of erosion and sedimentation zones, restricted to the area restored since 2011 (one hectare). The channel that drains the former main pond (Figs. 2F, 3 and 5) has experienced limited incision, but is not included in the erosion-sedimentation analysis, due to its function for draining a saturated area with mass movement risk.

Fig. 10 shows the DoDs of the Somolinos quarry associated with the restoration process and with erosion-sedimentation that occurred post-restoration. The erosion–sedimentation monitoring is graphically depicted for the area restored in 2011 (see Fig. 5 and aerial views at Fig. 8) since it is the area where limited erosion zones were identified, and also coincides with the area of the longest evolution time span after site restoration. At this area, the DoD analysis shows the erosion occurred at localized zones, where surface runoff cut through a portion of slopes and channels.

Fig. 11 shows the limited erosion zones sediment yield evolution at the Somolinos quarry with time. In terms of erosion rates, annual sediment yield of the monitored area oscillated from 12.11 t ha^{-1} yr^{-1} (15.69 t ha^{-1} yr^{-1} cumulative) at the end of 2015 (half of the monitored period) to 0 t ha^{-1} yr^{-1} (8.55 t ha^{-1} yr^{-1} cumulative) for May 2020 (end of the monitoring period).

5. Discussion

5.1. Design

The ecological restoration plan included a GeoFluv-Natural Regrade geomorphic design, a proposal for spreading carbonatic colluvium as growth media, a soil amendment of local sheep manure, and a revegetation focused on soil protection against erosion by seeding a grasses mix. The main value of this strategy is its holistic synthesis of topography, soils and vegetation, which is still very scarce worldwide.

5.1.1. Execution

The Somolinos restoration was accomplished as designed and planned for almost the entire area, although minor design oversights and construction deviations effected up to 0.2% of the area. The deviations occurred at the first phase of topographic construction during June 2011 (one hectare). This tract is the first GeoFluv example constructed in Europe. Therefore, the original Somolinos 2011 1-ha also provides the longest monitoring period for a GeoFluv case in the whole European continent.

5.1.2. Landscape evolution and erosion monitoring

The landscape evolution has been monitored from 2011 to 2020 through time-lapse sequences of several oblique aerial photos. The first three (April 2011, June 2011 and May 2014) were obtained using aviator plane flights and the three latter (December 2015, November 2019 and May 2020) through unmanned aerial vehicle (drone) photographs. During the observation period, drone technology replaced human on-board procedures for data collection.

Different topographic surveys and sources were used for erosion monitoring, according to their availability. From a methodological point of view, the point resolution largely varied between them, yet as the erosion zones lacked any vegetation, the results are considered valid. SfM-UAV surveys are accurate when not obscured by vegetation, but not accurate where vegetation cover exists.

At the Somolinos restored area, the near total absence of erosion is noticeable for the whole area for the entire monitored period. Zones with vegetation cover did not experience erosion at all. Figs. 7 and 8 show the dense vegetation cover which protects the hillslopes. This means the combination of geomorphic designs, soil amendments and grass seeding were an effective soil protection measure. Likewise, the manure-free zone did not experience erosion. The geomorphic designs coupled with the high stoniness of the colluvium provided adequate soil protection. Erosion-sedimentation only occurred at specific localized zones, where surface runoff cut through a portion of the area built in 2011, at the foot of the highwall. The evolution of the sediment yield of the Somolinos quarry with time confirms that these limited erosion zones started to stabilize five years after restoration, reaching steady-state stability after nine years.

In order to understand the process of limited erosion-sedimentation, we performed the following comparative analyses: (a) of the designed hillslope and channel longitudinal profiles with the as-built ones; and b) of channel tractive forces, re-evaluating in detail the runoff entering from additional watersheds.

The tractive force in a channel is the weight of water against the wetted perimeter of the stream bed on a given slope. It is a measure of the energy of the stream discharge against the stream bed. Tractive force can be compared to sediment particle size to give an indication of the force associated with sediment transport in a stream of interest. The weight of the water is a function of water volume, water density, and the force of gravity. Since water density and the force of gravity can be considered essentially constants, the volume of water is the functional variable. A unit volume of water can be determined from the stream discharge, which is volume per time. The wetted perimeter can be determined for different stream stages, for example at bankfull and flood-prone discharges. The channel slope can be calculated from its longitudinal profile. It can be seen then that for a particular channel, stream tractive force is mainly the product of slope and discharge. Increasing slope for a given discharge will increase tractive force.

Fig. 6. (a) Staking out the geomorphic design with DGPS; (b) D6 bulldozer regrading a scalloped hillslope; (c) excavator building a rock outcrop at the top of a ridge, to add geomorphic landscaping features; (d) excavator loading carbonatic colluvium to be used as subsoil; (e) mounds of carbonatic colluvium (white ellipse) being spread at the regraded surface; (f) mounds of organic matter (local sheep manure); (g) manual seeding and raking; (h) the white ellipse shows a local base level located at a stable sandstone ledge, visible at its right. This outcrop was also maintained, retaining geodiversity.

Fig. 7. Comparison of oblique aerial photos of the Somolinos quarry from April 2011 (before restoration) to May 2020. Notice the 1-ha surface restored in June 2011. At the May 2014 photo, the lighter colours (white arrow) are the central area left without manure amendment. Photos by Paisajes Españoles (years 2011 and 2014), David Gutiérrez (DGDRONE, years 2015 and 2020) and Javier Melero (year 2019).

Increasing discharge on a given slope will increase tractive force. Increasing both slope and discharge will increase tractive force. We selected a tractive force value of 12 kg m^{-2} as being associated with sediment movement in streams with similar particle size distribution as the project area.

Fig. 12 shows the main results of our scrutiny, which allowed identifying minor design and building oversights, and changes in tractive forces. We identified a 2-ha zone delivering runoff to this area that was not included in the design. That extra discharge, coupled with the longitudinal profile convexity and steepness, elevated the tractive force values enough to cause the limited erosion in this area. In all cases, the values surpassed the threshold of 12 kg m^{-2} that we set as a project stability threshold. Hydrologists have not yet determined a definite predictive formula for stream bedload transport prediction (Whitaker and Potts, 2007). We set the threshold value by comparing the calculated bankfull discharge tractive force values to the sediment distribution on recently transported stream bed sediment in stable reference streams, and assumed that the particles in the d_{50} to d_{85} range and coarser would not move at that discharge and would provide stable channel substrate. Our interpretation, however, is not that the increase of tractive forces was the only factor causing limited erosion, but a combination of it with the minor design and building oversights.

Fig. 8. Nine years of landscape and vegetation evolution at the Somolinos quarry. The three upper images show progression from April 2011 (pre-restoration), to June 2011 (after first phase of geomorphic restoration, with the GeoFluv channels highlighted), to May 2020. The two lower images show vegetation evolution after an homogeneous (seeding) revegetation, with a divergence in community composition and structure among habitats ruled by the environmental heterogeneity provided by the geomorphic design (see text for explanation). Credits of aerial photos at Fig. 7 caption.

Although the eroded areas were a very small part of the project, we present these analyses as lessons learnt from these minor deviations, as a global contribution, so these nonconforming erosion zones can be anticipated and avoided. It is important:

(a) At the design phase within GeoFluv-Natural Regrade, to check proper convex-concave slopes and concave channel profiles. Here the beginning of the valley wall profile was not at the top of a ridge, but at the base of a steep mesa indicating that the concave profile should begin there, instead of after a convex profile.
(b) At the design phase within GeoFluv-Natural Regrade, to consider carefully any adjacent watershed zones delivering runoff to the designed areas, checking properly the tractive forces in the draft design, and discarding any design with values above the user's criterion. A proper GeoFluv design should verify that all channel reaches have tractive force values which satisfy the specified design criterion, so excess sediment transport (erosion) does not occur.

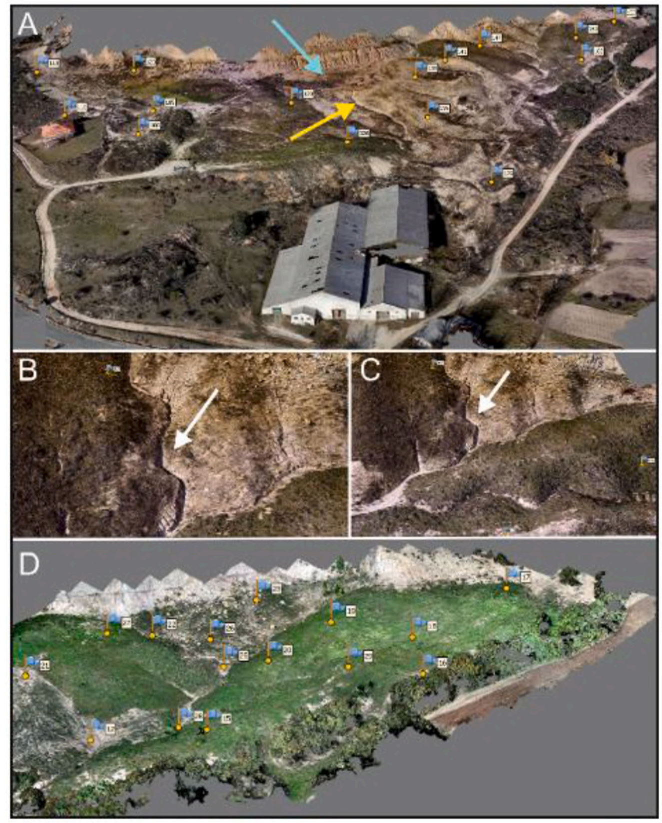

Fig. 9. 3D views of the point cloud for the SfM-UAV surveys in 2015 (A, B and C) and 2020 (D). (A) The blue arrow shows the former main sediment pond; the yellow one is its drainage line. The identified and studied erosion zones are evident at the B and C images (white arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(c) Using Landscape Evolution Models, such as SIBERIA. Indeed, SIBERIA modelling can anticipate (forecast) such erosion by modelling the GeoFluv designs in advance. Hancock et al. (2019) provide an example for the Hunter Valley in New South Wales.
(d) Ensuring all specified tolerances are held when constructing the design.

In this regard, it is critical to bear sharply in mind that soil erosion models cannot predict such channel erosion vulnerability. Indeed, the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978) and its derivatives, such as the Revised Universal Soil Loss Equation (RUSLE, Toy and Foster, 1998), have been used globally for many decades to forecast soil erosion, including at mine sites. Other models such as the Water Erosion Prediction Program (WEPP) are widely used to model soil erosion in mine rehabilitation (Flanagan and Livingston, 1995). However, these models do not adequately consider gully erosion, and therefore, cannot be used to solve problems as the one referred here. This example emphasizes the unsuitability of modelling erosion at mine sites only with soil erosion models (suitable for a hillslope scale) whereas for large areas (landscape scale, common in mines), concentrated flows of significant magnitude will always occur, and a more robust method, forecasting gullying, is needed.

We interpret that the localized erosion that occurred at Somolinos was caused by specific minor dysfunctions that can be corrected in similar future projects, by simply watching over proper designs and building criteria, by taking care to include precisely all sources of run-on

Table 3
Topographic changes in the Somolinos quarry through time.

DoD	Date of topography		Years	Cumulative years	Cause of topographic change	Excavation/erosion	Accumulation/deposition	Total sediment yield
	Initial	Final				m^3 (+/− %)		t (+/− %)
1	1963	29.01.2010	n.a.	n.a.	Mining activity	180,000 (36)	85,000 (45)	n.a.
2	29.01.2010	11.12.2015[a]	n.a.	n.a.	Restoration	15,200 (13)	26,500 (17)[b]	n.a.
3	28.06.2011	26.03.2012	0.7	0.7	Evolution of the restored area	11.6 (21)	8 (29)	5.04 (95)
4	26.03.2012	11.12.2015	3.7	4.4		44.8 (13)	1.5 (28)	60.62 (14)
5	11.12.2015	01.10.2019	3.8	8.2		6.8 (35)	3.2 (40)	5.04 (77)
6	01.10.2019	17.05.2020	0.6	8.8		0 (0)	0 (0)[c]	0 (0)

DoD	Date of topography		Years	Cumulative years	Cause of topographic change	Annual	Cumulative	Average erosion depth
	Initial	Final				Sediment yield		
						$t\ ha^{-1}\ yr^{-1}$ (+/− %)		m (+/− %)
1	1963	29.01.2010	n.a.	n.a.	Mining activity	n.a.	n.a.	n.a.
2	29.01.2010	11.12.2015[a]	n.a.	n.a.	Restoration	n.a.	n.a.	n.a.
3	28.06.2011	26.03.2012	0.7	0.7	Evolution of the restored area	7.74 (95)	6.77	−0.02 (95)
4	26.03.2012	11.12.2015	3.7	4.4		12.11 (14)	16.05	−0.19 (14)
5	11.12.2015	01.10.2019	3.8	8.2		1.43 (77)	9.20	−0.14 (77)
6	01.10.2019	17.05.2020	0.6	8.8		0 (0)	8.55	0 (0)

The variations in erosion and sedimentation refer to the area restored in 2011 (0.93 ha). A bulk density of 1.4 g cm^{-3} was used to convert volume to mass. Excavation and Accumulation refer to human earth movements (mining activity and restoration) and erosion and deposition to the natural evolution of the restored area (channel incision)

n.a. – non applicable.

[a] Since the restoration was carried out in two phases, Summer 2011 and Autumn 2013, the topography used to make this calculation was that from 2015.

[b] We interpret the difference between cut and fill volumes involved in the restoration is due to both the importing of carbonatic colluvium as growth media and because of the swell factor when excavating consolidated waste dumps.

[c] A real value of 13.5 (35) was obtained, but it was demonstrated that it was due to vegetation.

water, and by inspecting channel tractive force values during the design stage. In any case, 99.8% of the area presents no indication of accelerated erosion when walked and surveyed. If we extrapolate the erosion values to the whole area, in terms of mass of sediment yield per hectare per year, which is a universal indicator, we argue that such values are still low. For the whole period of nine years (June 2011 to May 2020), the value is 8.55 t ha^{-1} yr^{-1}. This value can be considered:

(a) Successful for mined restored areas, although references for such aim are surprisingly low in the literature. Among the very few of them, the Australian Queensland Department of Mines and Energy uses a range of 12–40 t ha^{-1} yr^{-1} as a target erosion rate for rehabilitated mine sites (Welsh et al., 1994; Williams, 2000).

(b) Equivalent to other GeoFluv-based restorations, such as 4.02 t ha^{-1} yr^{-1} (Zapico et al., 2018) and for an equivalent scenario) and 5.64 t ha^{-1} yr^{-1} for a GeoFluv-Natural Regrade restoration in New Mexico (Bugosh and Epp, 2019).

(c) Below 11.2 t ha^{-1} yr^{-1}, which is generally considered as the maximum threshold for annual soil erosion in agricultural lands (Schmidt et al., 1982; FAO, 1988). However, we emphasize that we are using this value as mere comparison, since, as we are stressing, this value would be applicable for widespread hillslope erosion, whereas we are reporting minor and localized erosion lines, with no hillslope erosion at 99.8% of the whole surface of the restored Somolinos quarry.

It has to be considered, also, that we are not reporting a sediment yield, *sensu stricto*, from a restored area, because the quantified sediment yield is referred to the 2011 1-ha restored sector, which actually has the continuation of the GeoFluv designs downstream (see Fig. 5). Thus, the sediment that exited this area was stored at the channel bottoms downstream. An inspection of the whole design for the nine monitored years showed that no bedload exited the restored area, to the natural fluvial network. We have no evidences about suspended sediment concentration (SSC), but no turbidity pollution has been reported in the fluvial network downstream of the quarry since its restoration. Related with this issue, having temporary sediment traps is a recommended GeoFluv construction technique that can provide downstream protection until minimal erosion (baseline) rates are achieved, as a product of both vegetation colonization and some adjustments of the landscape following geomorphic-based restorations, which have been reported to be lower than with engineering approaches (Toy and Chuse, 2005).

5.1.3. Meaning of the erosion: relationship with amount and intensity of precipitation

The results of this section have been obtained from information yielded by the Spanish Weather Agency of the Minister of Agriculture, Food and Environment *(Agencia Estatal de Meteorología,* AEMET*)*. An analysis of annual precipitation for the weather station of La Riba de Escalote (#2059), closest weather station with a longer precipitation record (25 km to the northeast of Somolinos) shows that the average annual precipitation for the period 2011–2020 is slightly wetter-than-average. Average values (see Fig. 13) are: 1954–2010 (457 mm); 2011–2020 (463.4 mm); 1954–2020 (458 mm).

Regarding intensity, an analysis of the annual series, for the same period of 1954–2020, of maximum precipitation in 24-h duration shows, for two statistical models (SQRT-ETmax + ML y Gumbel + MOM), the different precipitation quantiles are slightly higher for the series 1954–2020 than for the series 1954–2010 (see Table 4 and Fig. 14). This means that the maximum precipitation in 24-h has increased for the decade 2011–2020. In addition, those percentages increase with the return period, between 3.1% ($T = 2$ years) and 6.3% ($T = 500$ years). The maximum precipitation in 24-h for the monitored period (2011−2020) corresponds to the year 2013, with 60.0 mm, which has a return period between 10 and 25 years for both statistical models. This means: (a) the monitored evolution has already experienced non-frequent events; and, (b) it is likely that this type of event will repeat in the next decade, compared to the precedent ones.

Therefore, as far as the relationship between the identified erosion zones at the Somolinos restored quarry and precipitation is concerned, we see the period 2011–2020 corresponds to slightly higher amounts of annual precipitation and higher intensities (maximum precipitation in 24-h). The increase of precipitation intensity is indeed coherent with the expected effects of Climate Change in Spain (MMA, 2005). This means the restored quarry of Somolinos might be, already, evolving under such climate impact. Since the eroded zones are shown as a steady-state stability after nine years of evolution, under escalating rainfall

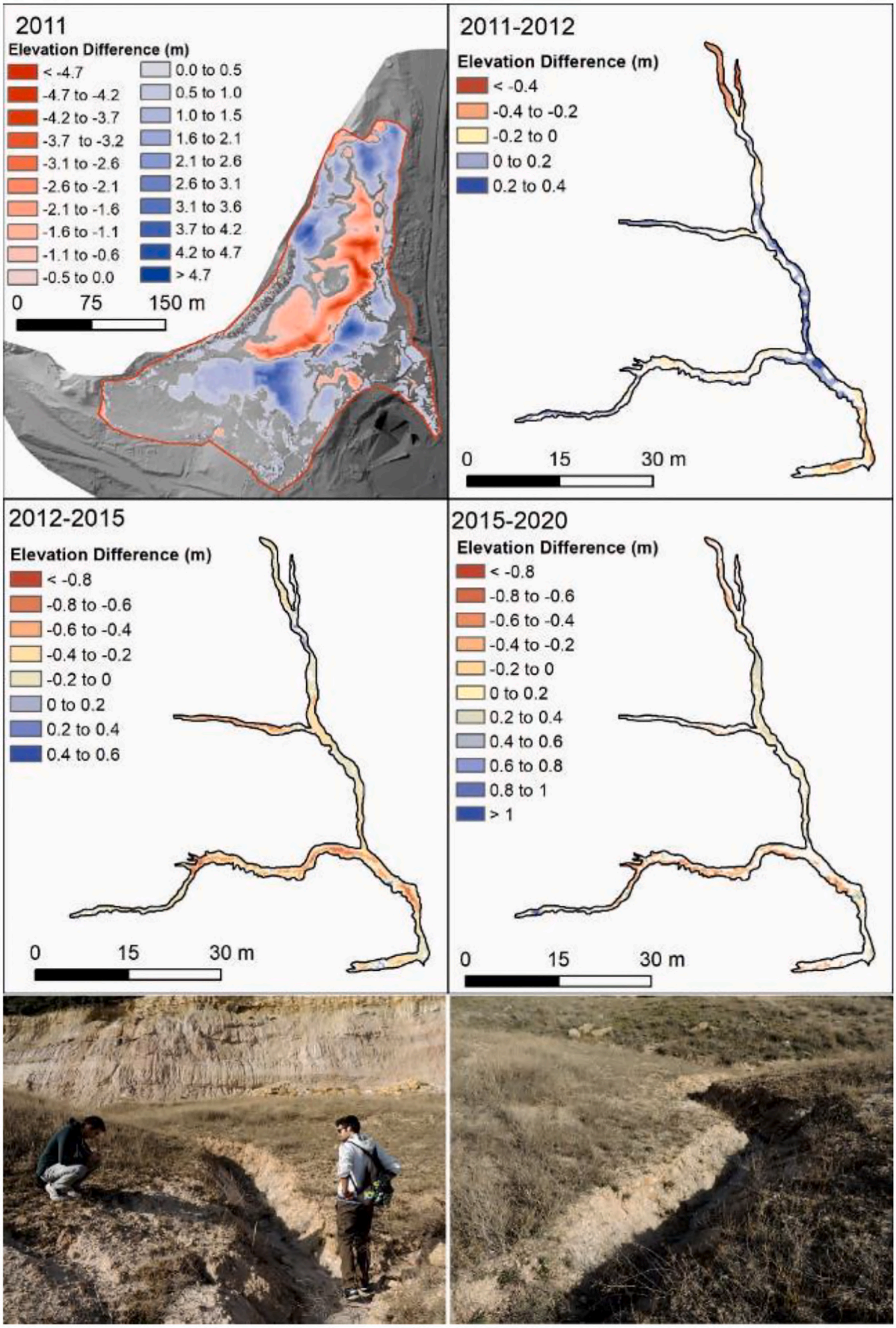

Fig. 10. DoDs of the Somolinos quarry for: 2011, earth movement involved in the geomorphic restoration process; and erosion and deposition for a limited area for the periods 2011–2012, 2012–2015, and 2015–2020. The two lower images show one of the identified erosion zones (the one above the scales bars at the figures) as of December 19, 2015.

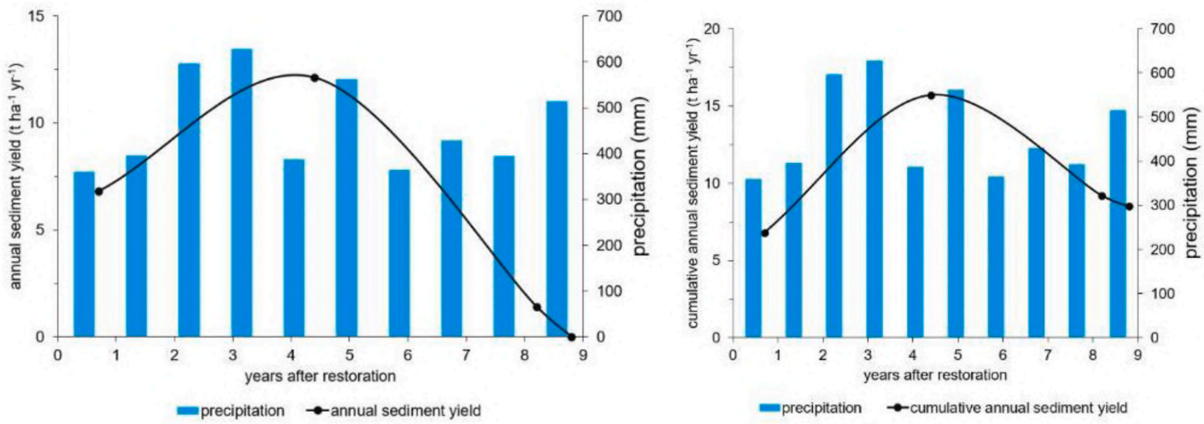

Fig. 11. Left, evolution of the annual sediment yield of the Somolinos quarry with time. Right, cumulative sediment yield for the Somolinos quarry. Precipitation values are included for informative purposes (see discussion on precipitation at 3.3.4 section).

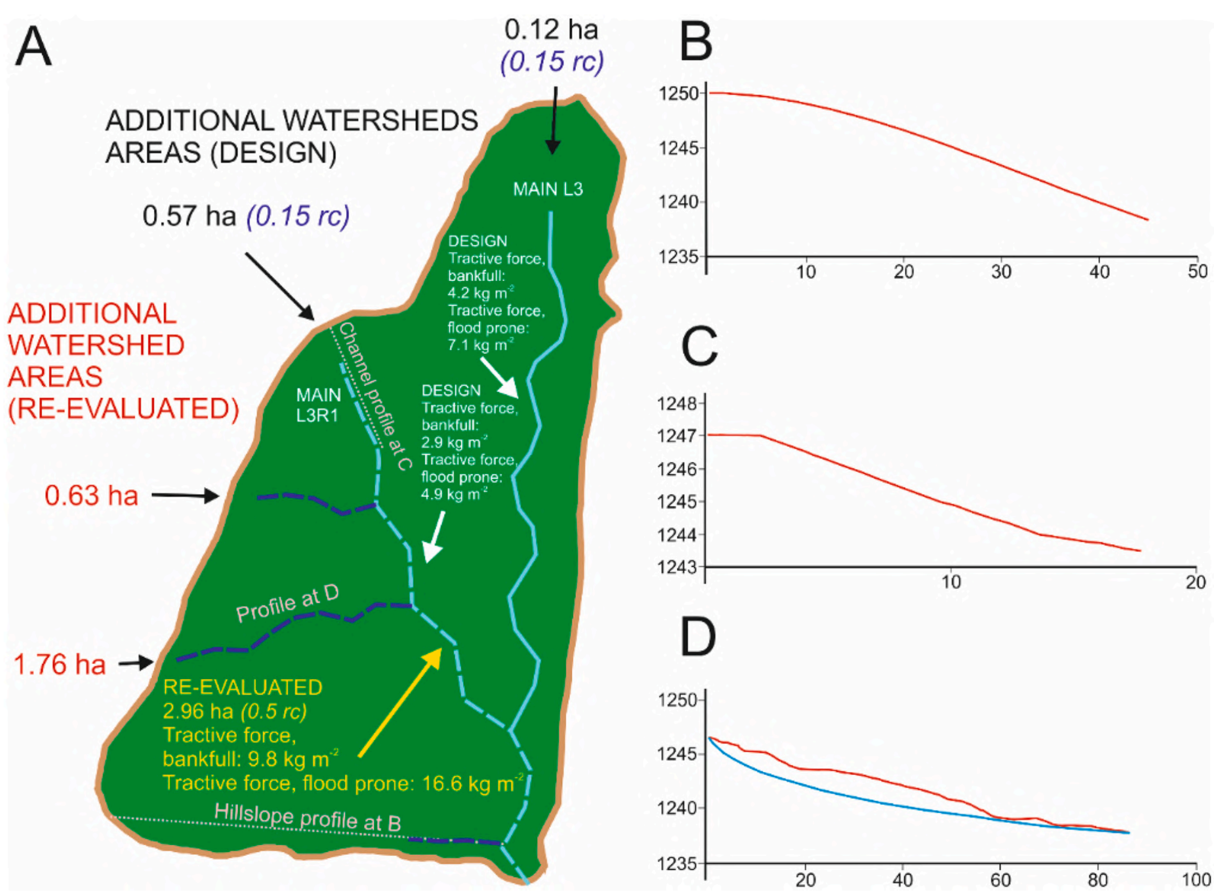

Fig. 12. (A) Area restored in June 2011 (see Figs. 8, 9 and 10) enclosing those areas that experienced erosion (dashed lines). Values in white are the tractive forces obtained at the design phase, and values in yellow those re-evaluated after the post-monitoring period (rc runoff coefficient). Main L3 means third left tributary of the main channel, and Main L3R1 means first right tributary of the third left tributary of the main channel. (B) Minor deviations in the design process. Longitudinal profile of a valley-wall slope—the longitudinal profile is predominantly convex and lacks a concave base. (C and D) Minor deviations in the construction process. The longitudinal profile of Main L3R1 has a long constant— gradient portion in its upper reaches which transitions to a flatter lower portion that forms a roughly concave longitudinal profile. It does show a knickpoint at its uppermost reach which appears to coincide with the greater erosion shown for the initial years of 2011–2012. (D) comparison between the as-built topography and the typical idealized (concave blue line) predominantly concave profile characteristic of stable landforms. For B, C and D; Y axe, elevations at m.a.s.l.; X axe, distance (m) at origin of profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

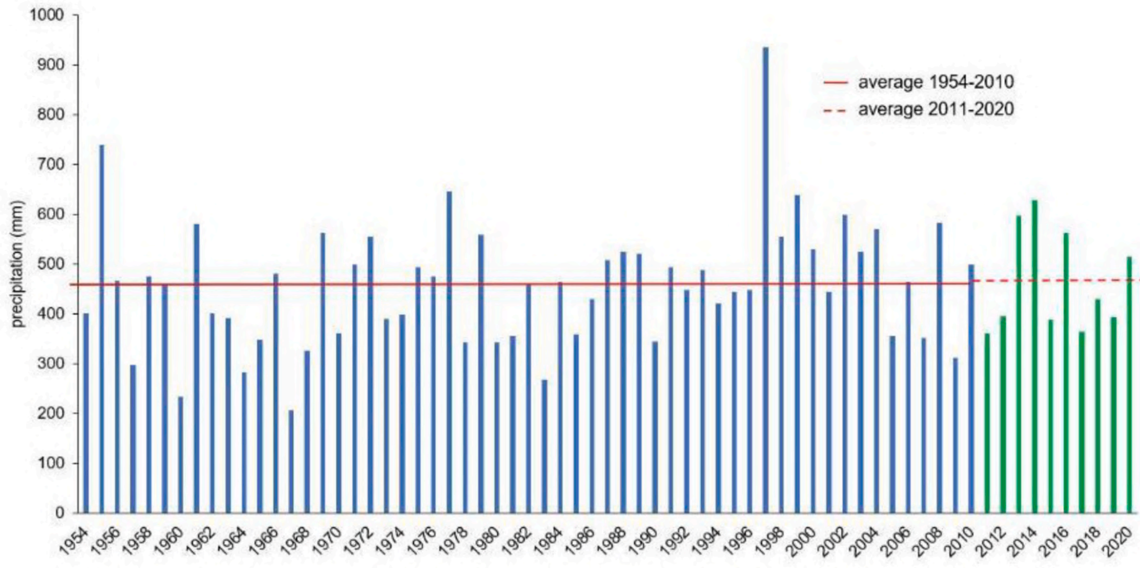

Fig. 13. Annual precipitation for the weather station of Riba de Escalote. This is the closest weather station to Somolinos (25 km northeast) with the longer precipitation record. Average values are: 1954–2010 (457 mm); 2011–2020 (463.4 mm); 1954–2020 (458 mm).

Table 4
Magnitude and frequency values of Maximum Precipitation in 24-h for the Riba de Escalote weather station.

Data series	Statistical model		Daily maximum precipitation (mm) for each return period (T, years)							
	Function	Method	T = 2	T = 5	*T* = 10	*T* = 25	T = 50	*T* = 100	*T* = 200	T = 500
1954–2010	SQRT-ETmax	ML	32	44	53	65	75	85	96	111
	Gumbel	MOM	32	43	49	58	64	70	77	85
1954–2020	SQRT-ETmax	ML	33	46	55	68	78	90	102	118
	Gumbel	MOM	34	45	52	61	68	75	82	91

conditions, an intensification of climate change effects is not expected to modify this established tendency to stability. It also has to be considered the GeoFluv method takes its geomorphic input values from mature, stable reference landforms which have developed over long periods of time, here in southern Europe over the last 10,000–12,000 years, during which there has been far greater climate variability than we report here. This gives a high degree of confidence that the restoration landforms will perform like the stable reference areas.

5.1.4. *Significance of the Somolinos quarry restoration*

The lessons learned from this case have a significant value, due to the length of the monitoring period. Due to its proven stability, complemented with experience from other examples in Spain, the European Commission has recognized Geomorphic Restoration among the Best Available Techniques for the Management of Waste of the Extractive Industries (JRC, 2018).

The Somolinos quarry occupied what is classified in Spain as a “Public Utility Forests” *(Monte de Utilidad Pública,* MUP*)*, with some degree of protection due to the environmental goods and services that they deliver to society. The confirmed healing of this piece of land will allow new land uses within such philosophy, for all people, for the future.

6. Conclusions

Although the example described here is local, it has a global contribution regarding its approach to: (a) understand, characterize and quantify the most possible complete history of land transformation and degradation for a specific site; (b) showing a methodology for holistic ecological restoration, for land healing; (c) identifying and understanding causes of deviation from absolute restoration success, in terms of erosion, from minor topographic design oversights, construction errors with landforms built slightly unsuited to grade, and underestimated runoff entering to the restored areas. This land restoration site elucidation (demonstration) provides paths to both identify and correct soil loss causations at the design phase and for solving them also at the building stage.

The monitoring of the geomorphic-based ecological restoration of the Somolinos quarry reveal the following conclusions: (a) landscape healing and divergence in vegetation community composition and structure, after an homogeneous seeding treatment, ruled by the environmental heterogeneity provided by to the geomorphic design; (b) absence of hillslope and channel erosion for 99.8% of the area for the whole monitored period; (c) limited erosion zones (0.2% of the area) were identified.

Specifically, the geomorphic-based ecological design performed as planned for the entire 6-ha project except for a localized zone of approximately 0.01 ha in which surface runoff cut through a portion of the restored surface. Analysis allowed those identified limited erosion zones to be ascribed to a combination of: (a) minor design oversights; (b) construction errors, with landforms that were built unfitted to grade; and, (c) excess of runoff entering the designed area, or unfit planned discharge. These limited identified erosion zones started to stabilize five years after initial restoration, reaching steady-state stability after nine years of restoration. The fact that only 0.2% of the restored landform surface showed any indications of accelerated erosion speaks to the robustness of the restoration method.

The main lesson learnt from these minor deviations, as a global contribution, is that such erosion zones can be avoided and anticipated at the design phase within GeoFluv-Natural Regrade by checking proper

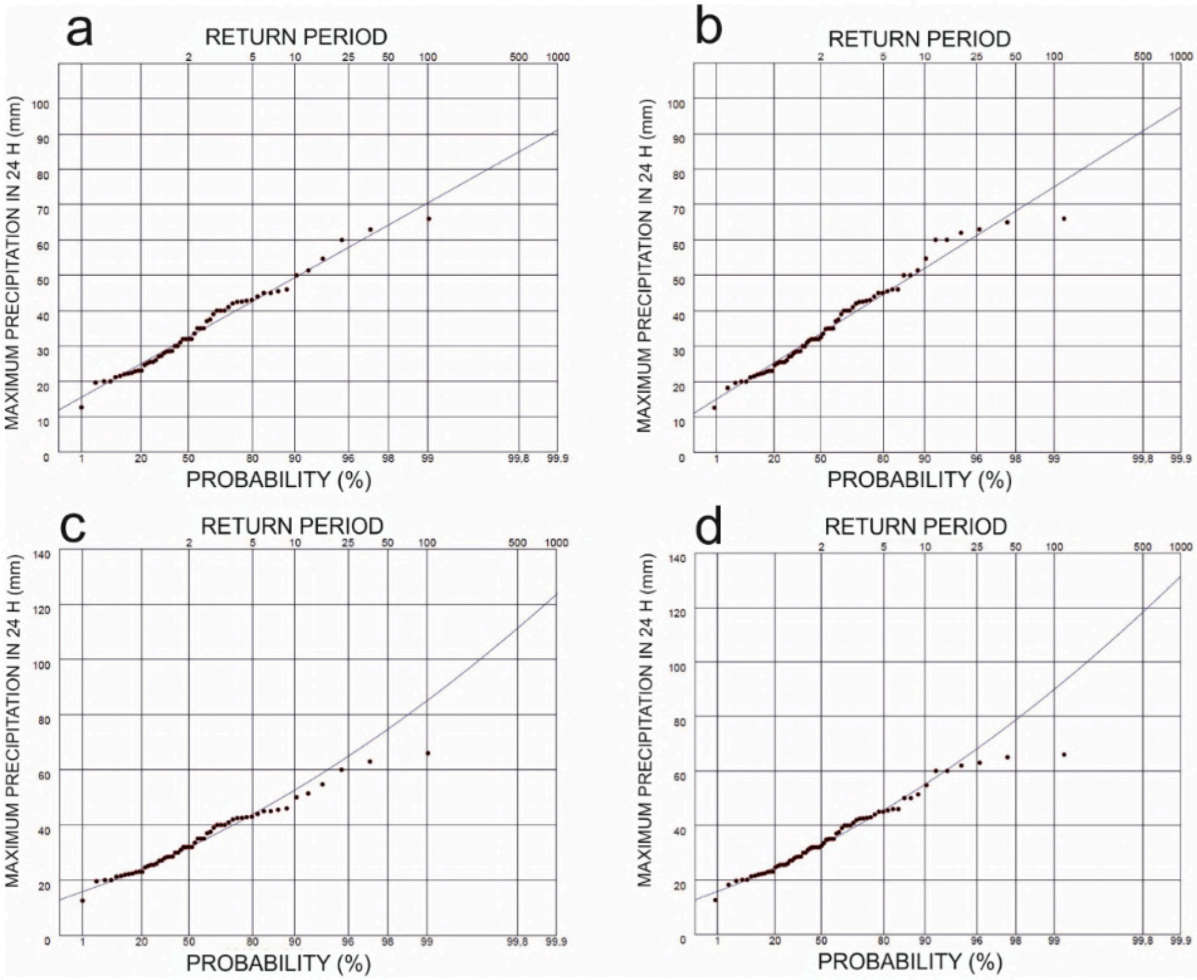

Fig. 14. Magnitude and frequency curves of Maximum Precipitation in 24-h for the Riba de Escalote weather station. (a) Gumbel function, MOM method, 1954–2010; (b) Gumbel function, MOM method, 1954–2020; (c) SQRT ETMax function, ML method, 1954–2010; (d) SQRT ETMax function, ML method, 1954–2020. See text and Table 4 for interpretation.

convex-concave hillslope and concave channel profiles and by considering carefully any additional watershed delivering runoff to the restoration designed areas, which influence the channel tractive forces. The use of Landscape Evolution Models, such as SIBERIA can also forecast such vulnerability, allowing avoiding it. After rigorously inspecting the design, it is imperative that the construction is completed true to the design by defining and adhering to construction tolerances.

A precipitation analysis for the area shows very minor increase in total annual rainfall and increase of rainfall intensity for the monitored period, 2011–2020, compared with the longest historical record of precipitation for the zone (1954–2020). The latter is coherent with the expected effects of climate change in Spain. We interpret therefore that the restored quarry of Somolinos might be already evolving under such global warming impact. Since the eroded areas have reached a state close to stability under such conditions after nine years of evolution, we forecast that an intensification of climate change effects is not expected to modify this tendency to stability. Overall, the reported results are considered robust, since they are an outcome of nine years of evolution of the restored area.

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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References

Bradshaw, A.D., Chadwick, M.J., 1980. The Restoration of Land. The Ecology and Reclamation of Derelict and Degraded Land. University of California Press, Berkeley.
Bugosh, N., 2000. Fluvial geomorphic principles applied to mined land reclamation. In: In: OSM Alternatives to Gradient Terraces Workshop, January 2000. Office of Surface Mining, Farmington.
Bugosh, N., 2003. Innovative reclamation techniques at San Juan Coal Company (or why we are doing our reclamation differently). In: July Rocky Mountain Coal Mining Institute National Meeting. Copper Mt.
Bugosh, N., Epp, E., 2019. Evaluating sediment production from native and fluvial geomorphic reclamation watersheds at La Plata Mine. Catena 174, 383–398. https://doi.org/10.1016/j.catena.2018.10.048.
Butler, D.R., 1995. Zoogeomorphology. In: Animals as Geomorphic Agents. Cambridge University Press, Cambridge.
Carrivick, J.L., Smith, M.W., Quincey, D.J., 2016. Structure from Motion in the Geosciences. Wiley-Blackwell, Hoboken, New Yersey.
CLM, 2020. Portal de Mapas de Castilla – La Mancha. https://castillalamancha.maps.arcgis.com/home/index.html. (Accessed 17 December 2020).
Cucchiaro, S., Cavalli, M., Vericat, D., Crema, S., Llena, M., Beinat, A., Marchi, L., Cazorzi, F., 2018. Monitoring topographic changes through 4D-structure-from-motion photogrammetry: application to a debris-flow channel. Environ. Earth Sci. 77 (18), 632. https://doi.org/10.1007/s12665-018-7817-4.
Currás, A., Zamora, L., Reed, J.M., García-Soto, E., Ferrero, S., Armengol, X., Mezquita-Joanes, F., Marqués, M.A., Riera, S., Julià, R., 2012. Climate change and human impact in Central Spain during Roman times: High-resolution multi-proxy analysis of a tufa lake record (Somolinos, 1280 m asl). Catena 89, 31–53. https://doi.org/10.1016/j.catena.2011.09.009.
Dotterweich, M., 2013. The history of human-induced soil erosion: Geomorphic legacies, early descriptions and research, and the development of soil conservation—a global synopsis. Geomorphology 201, 1–34. https://doi.org/10.1016/j.geomorph.2013.07.021.
FAO, 1988. Tillage Systems for Soil and Water Conservation, FAO Soils Bulletin 54. FAO, Rome.
Flanagan, D.C., Livingston, S.J., 1995. Water erosion prediction project (WEPP) version 95.7 user summary. In: Flanagan, D.C., Livingston, S.J. (Eds.), WEPP User Summary, NSERL Report No 11, July 1995.
GCD, 2018. Geomorphic Change Detection Software, Version 7.1.1.0 [WWW Document]. http://gcd.riverscapes.xyz/ (accessed 29 December 2020).
Gong, C., Lei, S., Bian, Z., Liu, Y., Zhang, Z., Cheng, W., Gong, C., Lei, S., Bian, Z., Liu, Y., Zhang, Z., Cheng, W., 2019. Analysis of the development of an Erosion Gully in an open-pit coal mine dump during a winter Freeze-Thaw Cycle by using low-cost UAVs. Remote Sens. 11, 1356. https://doi.org/10.3390/rs11111356.
Haigh, M.J., 1985. The experimental examination of hill-slope evolution and the reclamation of land disturbed by coal mining. In: Johnson, J.H. (Ed.), Geography Applied to Practical Problems. Geo Books, Norwich, pp. 123–138.
Hancock, G., Martín Duque, J.F., Willgoose, G., 2019. Geomorphic design and modelling at catchment scale for best mine rehabilitation – the Drayton mine example (New South Wales, Australia). Environ. Model. Softw. 114, 140–151. https://doi.org/10.1016/j.envsoft.2018.12.003.
Hancock, G.H., Martín Duque, J.F., Willgoose, G., 2020. Mining rehabilitation - using geomorphology to engineer ecologically sustainable landscapes for highly disturbed lands. Ecol. Eng. 155, 105836. https://doi.org/10.1016/j.ecoleng.2020.105836.
Hooke, R.L., Martín Duque, J.F., 2020. Impact of the Great Acceleration in our life-support systems. In: Schroder, J. (Ed.), Treatise on Geomorphology. Elsevier, Amsterdam.
IGN, 1961. Mapa Topográfico Nacional de España 1:50.000. Atienza. Hoja 433. Instituto Geográfico Nacional, Madrid.
IGN, 1995. Mapa Topográfico Nacional de España 1:25.000. Galve de Sorbe Hoja 433–3. Instituto Geográfico Nacional, Madrid.
JRC, 2018. Best Available Techniques (BAT) Reference Document for the Management of Waste from the Extractive Industries in Accordance with Directive 2006/21/EC, Publications Office of the European Union, Luxembourg.
Kelder, I., Waygood, C., Willis, T., 2016. Integrating the use of natural analogues and erosion modelling. In: Fourie, A., Tibbett, M. (Eds.), Mine Closure 2016. Australian Centre for Geomechanics, Perth, pp. 99–106.
Lucieer, A., de Jong, S.M., Turner, D., 2014. Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. Prog. Phys. Geogr. 38, 97–116. https://doi.org/10.1177/0309133313515293.
Martín Duque, J.F., Pedraza, J., Díez, A., Sanz, M.A., Carrasco, R.M., 1998. A geomorphological design for the rehabilitation of an abandoned sand quarry in Central Spain. Landsc. Urban Plan. 42 (1), 1–14. https://doi.org/10.1016/S0169-2046(98)00070-X.
Martín Duque, J.F., Sanz, M.A., Bodoque, J.M., Lucía, A., Martín-Moreno, C., 2010. Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes. Earth Surf. Process. Landf. 35, 531–548. https://doi.org/10.1002/esp.1950.
Martín Duque, J.F., Tejedor, M., Martín Moreno, C., Nicolau, Sanz Santos, M.A., Donoso, Sánchez, Gómez Díaz, J.M., 2020. Geomorphic landscape design integrated with progressive mine restoration in clay quarries of Catalonia. Int. J. Min. Reclam. Environ. 35 (6), 399–420. https://doi.org/10.1080/17480930.2020.1844368.
Martín-Moreno, C., Fidalgo Hijano, C., Martín Duque, J.F., González Martín, J.A., Zapico Alonso, I., Laronne, J.B., 2014. The Ribagorda sand gully (east-Central Spain): Sediment yield and human-induced origin. Geomorphology 224, 122–138. https://doi.org/10.1016/j.geomorph.2014.07.013.
Martín-Moreno, C., Martín Duque, J.F., Nicolau, J.M., Hernando, N., Sanz, M., Castillo, L., 2016. Effects of topography and surface soil cover on erosion for mining reclamation. The experimental spoil heap at El Machorro mine (Central Spain). Land Degrad. Dev. 27, 145–159. https://doi.org/10.1002/ldr.2232.
Martín-Moreno, C., Martín Duque, J.F., Nicolau, J.M., Muñoz, A., Zapico, I., 2018. Waste dump erosional landform stability – a critical issue for mountain mining. Earth Surf. Process. Landf. 43, 1431–1450. https://doi.org/10.1002/esp.4327.
MMA, 2005. A Preliminary General Assessment of the Impacts in Spain Due to the Effects of Climate Change. Ministerio de Medio Ambiente, Universidad de Castilla-La Mancha, Madrid.
Moreno De Las Heras, M., Nicolau, J.M., Espigares, T., 2008. Vegetation succession in reclaimed coal-mining slopes in a Mediterranean-dry environment. Ecol. Eng. 34 (2), 168–178. https://doi.org/10.1016/j.ecoleng.2008.07.017.
Nicolau, J.M., 2003. Trends in topography design and construction in opencast mining reclamation. Land Degrad. Dev. 14, 1–12. https://doi.org/10.1002/ldr.548V.
OSMRE, 2019. Geomorphic Reclamation. Office of Surface Mining, Reclamation and Enforcement, Department of Interior, US. http://www.osmre.gov/programs/tdt/geomorph.shtm (accessed 21 December 9).
PNOA, 2009. Plan Nacional De Ortofotografía Aérea, LiDAR De Castilla la–Mancha, Vuelo de 2009. Instituto Geográfico Nacional, Ministerio de Fomento, Madrid. http://pnoa.ign.es/. (Accessed 29 December 2020).
PNOA, 2019. Plan Nacional De Ortofotografía Aérea, LiDAR De Castilla la–Mancha, Vuelo de 2019. Instituto Geográfico Nacional, Ministerio de Fomento, Madrid. http://pnoa.ign.es/. (Accessed 29 December 2020).
Qcoherent software LLC, 2015. LP360 Advanced Level. (Version 2015.1.76.7).
Rosgen, D.L., 1994. A classification of natural rivers. Catena 22 (3), 169–199. https://doi.org/10.1016/0341-8162(94)90001-9.
Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs.
Sawatsky, L., Beckstead, G., 1996. Geomorphic approach for design of sustainable drainage systems for mineland reclamation. Int. J. Min. Reclam. Environ. 10 (3), 127–129.
Sawatsky, L., Beersing, A., 2014. Configuring Mine Disturbed Landforms for Long-Term Sustainability, in: Proceedings of Mine Closure Solutions, 2014, April 26–30, 2014, Ouro Preto, Minas Gerais, Brazil, pp. 1–13.
Schmidt, B.L., Allmaras, R.R., Mannering, J.V., Papendick, R.I., 1982. Determinants of Soil Loss Tolerance. American Society of Agronomy-Soil Science Society of America, Madison.
Schumm, S.A., Rea, D.K., 1995. Sediment yield from disturbed earth systems. Geology 23 (5), 391–394. https://doi.org/10.1130/0091-7613(1995)023<0391:SYFDES>2.3.CO;2.
SMCRA, 1977. Surface Mining Control and Reclamation Act, Public law, 95–87, Statutes at Large, 91 Stat. 445. Federal Law. US Government, United States.
Sonter, L.J., Dade, M.C., Watson, J.E.M., Valenta, R.K., 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nat. Commun. 11, 4174. https://doi.org/10.1038/s41467-020-17928-5.
Stiller, D.M., Zimpfer, G.L., Bishop, M., 1980. Application of geomorphic principles to surface mine reclamation in the semiarid West. J. Soil Water Conserv. 35 (6), 274–277.
Toy, T.J., Black, J.P., 2000. Topographic reconstruction: The theory and practice. In: Barnishel, R., Darmody, R., Daniels, W. (Eds.), Reclamation of Drastically Disturbed Lands. American Society of Agronomy, Madison, pp. 41–75.
Toy, T.J., Chuse, W.R., 2005. Topographic reconstruction: a geomorphic approach. Ecol. Eng. 24, 29–35. https://doi.org/10.1016/j.ecoleng.2004.12.014.
Toy, T.J., Foster, G.R., 1998. Guidelines for the Use of the Revised Universal Soil Loss Equation (RUSLE) version 1.06 on Mined Lands, Construction Sites and Reclaimed Lands. Office of Surface Mining, Denver.
Toy, T.J., Hadley, R.F., 1987. Geomorphology and Reclamation of Disturbed Lands. Academic Press, London.
UNEP, 2019. New UN Decade on Ecosystem Restoration Offers Unparalleled Opportunity for Job Creation, Food Security and Addressing Climate Change. United Nations Environment Program. https://www.unenvironment.org/news-and-stories/press-release/new-un-decade-ecosystem-restoration-offers-unparalleled-opportunity.
Vidal-Macua, J.J., Nicolau, J.M., Vicente, E., Moreno-De Las Heras, M., 2020. Assessing vegetation recovery in reclaimed opencast mines of the Teruel coalfield (Spain) using Landsat time series and boosted regression trees. Sci. Total Environ. 717, 137250. https://doi.org/10.1016/j.scitotenv.2020.137250.
Wade, T.G., Riitters, K.H., Wickham, J.D., Jones, K.B., 2003. Distribution and causes of global forest fragmentation. Conserv. Ecol. 7 (2), 7. http://www.consecol.org/vol7/iss2/art7.
Waygood, C., 2014. Adaptive landform design for closure. In: Weiersbye, I.M., Fourie, A. B., Tibbet, M., Mercer, K. (Eds.), Mine Closure 2014. University of the Witwatersrand, Johannesburg, pp. 1–12.

Welsh, D., Hinz, R., Garlipp, D., Gillespie, N., 1994. Coal mines on target with environmental planning. Queensl. Govern. Min. J. 94, 19–22.

Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2009. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf. Process. Landf. 35 (2), 136–156. https://doi.org/10.1002/esp.1886.

Whitaker, A.C., Potts, D.F., 2007. Analysis of flow competence in an alluvial gravel bed stream, Dupuyer Creek, Montana. Water Resour. Res. 43, W07433 https://doi.org/10.1029/2006WR005289.

Williams, D., 2000. Assessment of embankment parameters. In: Hustrulid, W.A., McCarter, M.K., Van Zyl, D.J.A. (Eds.), Slope Stability in Surface Mining. SME - Society for Mining, Metallurgy and Exploration, Littleton, pp. 275–284.

Williams, R.D., 2012. DEMs of difference. In: Clarke, L., Nield, J.M. (Eds.), Geomorphological Techniques. British Society for Geomorphology, London, pp. 1–17.

Williams, R.D., Bangen, S., Gillies, E., Kramer, N., Moir, H., Wheaton, J., 2020. Let the river erode! Enabling lateral migration increases geomorphic unit diversity. Sci. Total Environ. 715, 136817. https://doi.org/10.1016/J.SCITOTENV.2020.136817.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. In: A Guide to Conservation Planning. US Department of Agriculture Agriculture Handbook No. 537.2., Washington D.C.

Xiang, J., Chen, J., Sofia, G., Tian, Y., Tarolli, P., 2018. Open-pit mine geomorphic changes analysis using multi-temporal UAV survey. Environ. Earth Sci. 77, 220. https://doi.org/10.1007/s12665-018-7383-9.

Xiang, J., Li, S., Xiao, K., Chen, J., Sofia, G., Tarolli, P., Xiang, J., Li, S., Xiao, K., Chen, J., Sofia, G., Tarolli, P., 2019. Quantitative analysis of anthropogenic morphologies based on multi-temporal high-resolution topography. Remote Sens. 11, 1493. https://doi.org/10.3390/rs11121493.

Zapico, I., Martín Duque, J.F., Bugosh, N., Laronne, J.B., Ortega, A., Molina, A., Martín-Moreno, C., Nicolau, J.M., Sánchez Castillo, L., 2018. Geomorphic Reclamation for reestablishment of landform stability at a watershed scale in mined sites: the Alto Tajo Natural Park, Spain. Ecol. Eng. 111, 100–116. https://doi.org/10.1016/j.ecoleng.2017.11.011.

Zapico, I., Molina, A., Laronne, J., Sánchez, L., Martín Duque, J.F., 2020. Stabilization by geomorphic reclamation of a rotational landslide in an abandoned mine next to the Alto Tajo Natural Park. Eng. Geol. 264, 105321. https://doi.org/10.1016/j.enggeo.2019.105321.