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Geomorphic reclamation for reestablishment of landform stability at a watershed scale in mined sites: The Alto Tajo Natural Park, Spain

Ignacio Zapico[a,b,*], José F. Martín Duque[a,b], Nicholas Bugosh[c], Jonathan B. Laronne[d], Ana Ortega[b], Antonio Molina[e], Cristina Martín-Moreno[b], José M. Nicolau[f], Lázaro Sánchez Castillo[g]

[a] Geoscience Institute, IGEO (CSIC, UCM), 28040 Madrid, Spain
[b] Geodynamics Department, Complutense University, 28040 Madrid, Spain
[c] GeoFluv, 2205 North Avenue, Parma, OH 44134, United States
[d] Department of Geography and Environmental Development, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel
[e] Centro de Astrobiología (INTA, CSIC), 28850 Torrejón de Ardoz, Madrid, Spain
[f] Department of Agrarian and Environmental Sciences, Technical School, University of Zaragoza, Huesca, E-22071, Spain
[g] Department of Geologic Engineering, Polytechnic University of Madrid, Madrid 28003, Spain

A R T I C L E I N F O

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A B S T R A C T

This research describes a geomorphic-based process of mining reclamation carried out at the El Machorro mine (at the edge of the Alto Tajo Natural Park, East Central Spain) and its monitoring for five years (2012–2017). The GeoFluv™ method implemented by the Natural Regrade software has been used to design small watersheds as a mining reclamation topographical solution. The procedure included: (i) finding a suitable reference area with stable landforms and acquiring inputs from them; (ii) designing two first-order stream watersheds; (iii) building the planned landscape; and (iv) monitoring the hydrological and erosive – sedimentary response of the reclaimed watersheds. This process is in itself a contribution to global advancement of reclamation best practices, because there are very few geomorphic-based mining reclamation examples, and even fewer that include their multi-annual monitoring. Sediment yields were obtained comparing Digital Elevation Models (DEM) acquired by Total Station (TS), Terrestrial Laser Scanning (TLS), differential Global Positioning System (GPS) and topographic reconstructions (interpretations). An H-flume with turbidity and water pressure sensors allowed quantifying runoff and suspended sediment. Sediment yield progressively decreased with time attaining a current low value (4.02 Mg ha^{-1} yr^{-1}). Water discharge and suspended sediment concentration have also decreased with time.

Initially, high sediment yield values were obtained. They are interpreted as being triggered by grading errors that deviated from the design, so that runoff adjusted construction irregularities during that period by erosion and sedimentation. After those adjustments, the reclamation surface became more reflective of the design and the resulting surface remained very 'stable'. The deduction is that the geomorphic-based reclamation has re-established an approximate steady-state or dynamic equilibrium, where hydrological and erosive – sedimentary functionality operate now at rates comparable to the surrounding natural land. Although further research is required to confirm long-term stability, geomorphic reclamation appears as an efficient mining reclamation alternative solution to the traditional approach of gradient terraces and downdrains, which require frequent and costly maintenance, in the highly erodible setting of the Alto Tajo Natural Park surroundings, as well as in most open pit mines.

1. Introduction

Surface mining impacts all ecosystem components: substrata, topography, surface hydrology and groundwater, soil, vegetation, fauna, atmosphere and landscape (Nicolau, 2003; Mossa and James, 2013; Martín Duque et al., 2015; Tarolli and Sofia, 2016). This causes many on-site effects. Soil erosion is one of the most significant ones, being a barrier to the success of restoration practices (Whisenant, 2005) and affecting vegetation growth through different mechanisms: the removal of seeds and nutrients from the topsoil, direct plant removal, and the loss of water resources through surface runoff (Pimentel et al., 1995; Moreno-de las Heras et al., 2008). Mining activities can also have

* Corresponding author at: Geoscience Institute, IGEO (CSIC, UCM), 28040 Madrid, Spain.
E-mail address: izapico@ucm.es (I. Zapico).

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downstream off-site effects, which can be very detrimental to the environment. Among these, the impact on water quality associated with high sediment loads discharged from mine pits, dumps or facilities to the fluvial system is one of the most harmful (Martín-Moreno et al., 2016; McIntyre et al., 2016; Messina and Biggs, 2016; Zapico et al., 2017). This is worse if acid mine drainage is involved.

Mining reclamation is expected to prevent both on-site and off-site impacts. Nonetheless, failures have been common in this regard, in spite of the significant development of reclamation techniques during the last decades. One of the reasons is that common topographic mining reclamation practices, like gradient terraces with downdrains, are not able to guarantee long-term landform stability (Haigh, 2000).

To achieve effective control of erosion and sedimentation in reclaimed mining areas and their surroundings, an integrated management of mining wastes, water, topography, surface soil cover and vegetation is required. Topographic reconstruction has not received the same attention as factors such as soil and vegetation (Nicolau, 2003). Thus, the common traditional approach to landform design involves terraced landforms – graded waste banks consisting of alternating short constant-gradient outslopes and benches. Without maintenance, many terraced landforms succumb to water erosion (Loch, 1997). Linear slopes are also unstable, due to lack of appropriate drainage density. A study of 57 reclaimed mines in North America illustrated that deficient drainage design was a common reason for failure of mine reclamation landscapes (McKenna and Dawson, 1997). Base level changes also cause reclamation failures, for instance by ditch incision, causing the upslope areas to respond by eroding or mass failure (e.g., Haigh, 1980, 1985). Erosion problems also arise because of ponding or exceeding the storage capacity of benches (Sawatsky et al., 2000).

Alternatively, another topographic approach to mining reclamation based on designs that replicate natural landforms and landscapes is growing in use (Bugosh, 2000; Hancock et al., 2003; Toy and Chuse, 2005; Schor and Gray, 2007; Martín Duque et al., 2010; DePriest et al., 2015). This can be generically termed 'geomorphic reclamation', which according to the Office of Surface Mining Reclamation and Enforcement of the United States allows designing *"stable landforms and streams that mimic both the look and the functionality of nature"*. Within this approach *"steep rock lined ditches are replaced by meandering streams and uniform or terraced hillsides are replaced by slopes that look natural yet are specifically designed to efficiently convey water without excessive erosion or sediment loading"* (OSMRE, 2016). Geomorphic reclamation is based on the scientific knowledge of geomorphic processes, mostly slope and fluvial ones operating for an extended time within drainage basins – the most common landscape organization on the Earth's surface.

Toy and Chuse (2005, p. 30) concisely summarize the aim of geomorphic reclamation: "*to build landscapes that will approximate to steady-state configurations, so that they will experience much less modification by earth surface processes after geomorphic reclamation than landscapes that do not approximate to steady-state configurations."* They further state, *"as the adjustments necessary to establish a steady-state decrease, the prospect for reclamation success increases and the demand for post-reclamation site maintenance decreases"*.

Geomorphic reclamation is becoming identified as Best Technology Currently Available (BTCA, United States) or Best Available Technique (BAT, European Union) within extractive industries. The New Mexico Mining and Minerals Division considers that a geomorphic approach to backfilling and grading is the BTCA for stabilizing coal mine reclamation. The Joint Research Centre of the European Union is recognizing geomorphic reclamation as BAT for the management of extractive industry wastes (JRC, 2016).

There are just a few procedures, to the best of our knowledge, for designing stable natural landforms at sites disturbed by earth movements. The Talus Royal method is being successfully applied at rock roadcuts in France (Génie Géologique, 2016). The Rosgen (1994, 1996) approach has been widely employed for perennial stream restoration in the United States, including mined sites. The GeoFluv™ method (Bugosh, 2000, 2003) has been and it is being used successfully for mining reclamation in the US, Australia, Colombia and Spain (see Bugosh et al., 2016). Increasing research seeks its spreading (DePriest et al., 2015). There are also very few Computer Aided Design (CAD) software products to design landforms that replicate the natural ones. RIVERMorph (2016) is based on the principles established by Rosgen (1994, 1996) and Natural Regrade is the computerized implementation of the GeoFluv method. RIVERMorph focuses on perennial streams, while GeoFluv-Natural Regrade focuses on reclaiming disturbed lands with uplands and streams integrated into functional watersheds of different sizes. The latter fits with the physiographic conditions of the Alto Tajo mines, the core of this research. Its use has allowed testing the reclamation landform stability for balanced erosive-sedimentary dynamics at a sub-watershed scale in the surroundings of the Alto Tajo Natural Park, Spain.

In addition, there are also a bountiful set of methods, models and software to evaluate the hydrological, erosive stability or evolution of both traditional and geomorphic reclamation solutions at mine sites. One method of validating the stability of mining reclamations is the use of common erosion models, such as RUSLE (Evans, 2000) or WEPP (West and Wali, 1999). Landscape Evolution Models (LEM), as SIBERIA or CAESAR-Lisflood, have been used to predict the geomorphic evolution of post-mining landscapes (Willgoose and Riley, 1998; Evans et al., 2000; Hancock et al., 2002, 2008, 2017). These models can offer good results with a proper calibration (Hancock et al., 2016).

However, few validating studies have been carried out based on direct field measurements for the purpose of determining the stability performance of different landforms in mining reclamation. These mostly correspond with plots at a slope scale (Merino-Martín et al., 2012; Lowry et al., 2014; Martín-Moreno et al., 2016; Hancock et al., 2016). Data from those field plots have an extraordinary value, as they are scarce in the literature. Nonetheless, such plots do not represent the complex behavior and landform stability of reclaimed landscapes. Entire hillslopes respond differently than slope plots and watersheds respond differently from single hillslopes due to patchiness, or interaction between hillslope and fluvial process (Lane et al., 1997; Verbist et al., 2010). Fig. 1 shows that the scale of mine reclamation erosion is often much larger than that of slope-scale erosion plots. This figure also reinforces the idea expressed by Willgoose and Riley (1998) that drainage network development is a chaotic process, which is the cause of many mining reclamation failures. According to the same authors, if an initial drainage pattern is imposed, predictability is exerted on the eroding system (Willgoose and Riley, 1998). The GeoFluv method actually uses this principle, with the aim of imposing non-eroding (steady-state) drainage networks for reclamation.

Several kaolin mines surround the Alto Tajo Natural Park (ATNP) in East-Central Spain. Because of the high erosive potential of this setting (loose sandy and clayed wastes, steep and long slopes and high rainfall erosivity), with a potential for increasing the sediment yield of the fluvial network of this valued ecological area, the mining company Caobar S.A. is seeking landform stability at their mines through geomorphic reclamations based on GeoFluv-Natural Regrade. The aim is restoring landform stability and balanced erosive-sedimentary dynamics of the reclaimed mine sites. This study describes and evaluates one of these reclamation projects and its monitoring for five years (2012–2017).

Given the provided introductory framework, the principal aims of this study are: (i) to describe the entire process of a fluvial geomorphic-based mining reclamation at El Machorro with GeoFluv-Natural Regrade; and (ii) to evaluate its landform stability through monitoring its hydrologic and erosive-sedimentary response at a small watershed scale. The hypothesis is that, by means of this fluvial geomorphic

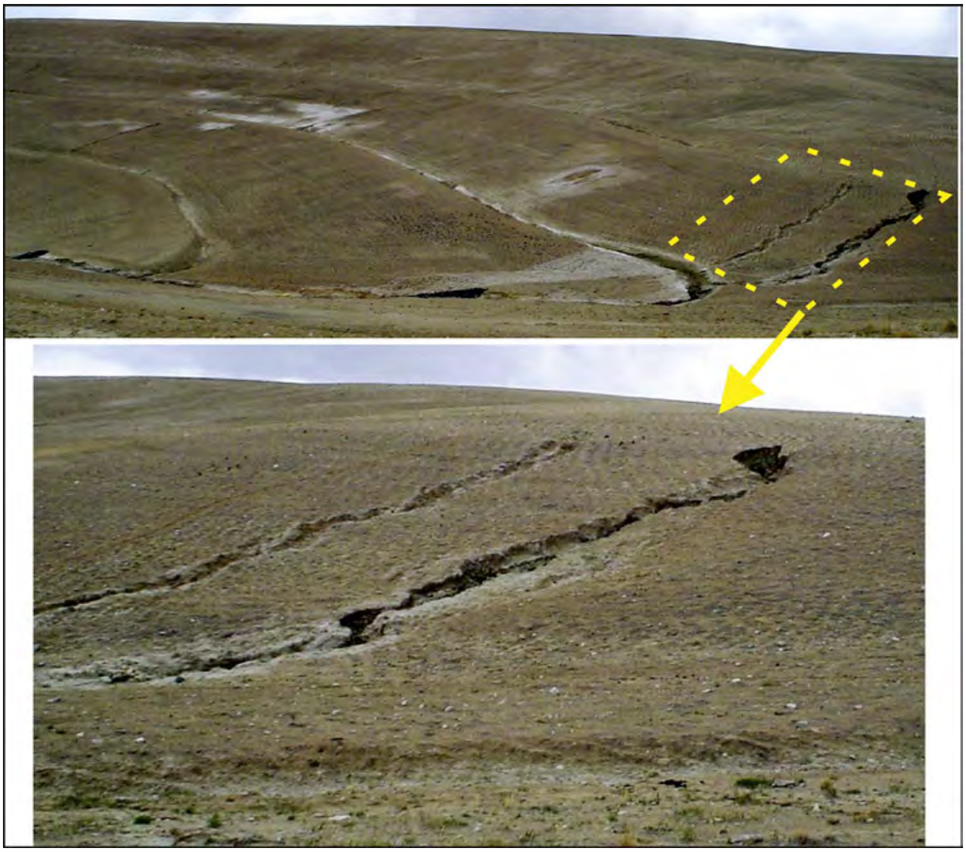

Fig. 1. Gully erosion of graded terraces at Gas Hills uranium district in Wyoming (US). Photo by Harold Hutson. An experiment to measure erosion at this site with slope plots, located away from areas affected by gullying, would reflect neither the actual erosion of the watershed nor the performance of the reclamation method.

method, an approximate steady state or dynamic equilibrium will be reestablished, so that hydrological and erosive – sedimentary functionality will operate at low rates conforming to nearby landform stability. The aim is to test the extent to which geomorphic reclamation may be a mining reclamation alternative to the traditional approach, having a permanent reduction in sediment yield from reclaimed areas, and therefore minimizing maintenance and runoff impacts from mining in this setting.

2. Materials and methods

2.1. Study area

2.1.1. Alto Tajo Natural Park (ATNP) and mining area

Several kaolin mines are located surrounding the ATNP in East-Central Spain (Fig. 2). This area is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones) underlain by sandy sediments that contain the kaolin (*Arenas de Utrillas*

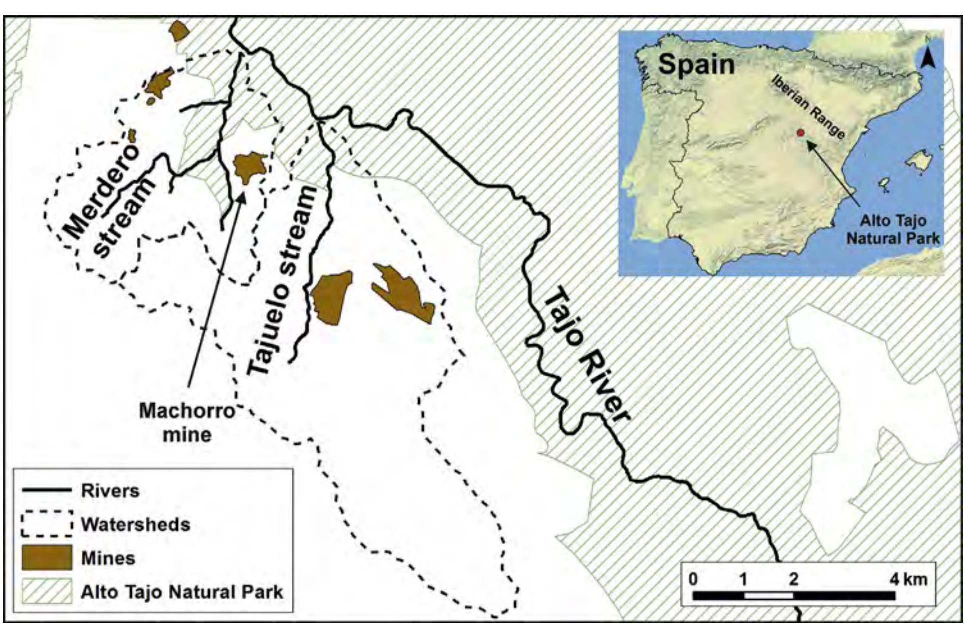

Fig. 2. Location of the mined areas at the edge of the Alto Tajo Natural Park.

Formation). The Tajo River has incised a canyon system into the plateaus; it is longer than 100 km and up to 400 m in depth (Carcavilla et al., 2011).

The most common soils draping this landscape are calcaric cambisols, mollic leptosols and rendzic leptosols on top of the mesas, and calcaric cambisols on carbonate colluvia on the slopes (IUSS Working group WRB, 2007). The vegetation is dominated by *Juniperus thurifera*, *Pinus nigra* subsp. *salzmannii* and *Quercus faginea* (MARM, 1997).

The climate is temperate Mediterranean with dry and mild summers (Csb, according to Köppen, 1918) and with continental influence. Mean annual precipitation is 783 mm and the mean annual temperature is 10 °C (AEMET, 2013). Seasonally, this area is characterized by long and cold winters with snow being common, and short, dry summers. The spring and autumn seasons are usually wet. The rainfall erosivity factor, R (equivalent to the R factor of RUSLE), is estimated to be about 800 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988).

2.1.2. El Machorro mine

El Machorro is one of two active mines in the Alto Tajo area, belonging to the Caobar company. It is located in the Merdero stream watershed (see Fig. 2). Beneficiation from this mine, and a nearby one, results in the highest and best-quality kaolin production of Spain. El Machorro is a slope mine with an exploitation method termed contour mining. An unpublished report (ADARO, 1983) includes a picture of the mesa-type hill where El Machorro mining began in the year 2000 (Fig. 3).

As an active mine, a large part of its surface is either dynamic open pit (Fig. 4a) or waste dumps (Fig. 4b). A system of ponds (Fig. 4c) control the runoff and sediments yielded by these active areas. Both runoff and sediment mostly derive from un-reclaimed waste dumps, which are subject to high runoff and active rilling and gullying (Fig. 5). The areas which are not active open pit or waste dumps have been reclaimed, displaying four different approaches of landform mining reclamation, from traditional to geomorphic (Fig. 4): (R1) terraces (linear outslopes – bench and downdrain systems) covered with carbonate colluvium, (R2) smoothed sloping terraces covered with carbonate colluvium, (R3) terraces covered both with carbonate colluvium and soils, and (R4) geomorphic reclamation using GeoFluv-Natural Regrade (this study site). R1 has hydro-seeding and planted trees (mostly pines), whereas R2 and R3 have manual seeding and planted shrubs and trees.

This mine also has an experimental mining reclamation waste dump (ER), in which the sediment yield from a combination of two morphologies (linear and concave slopes) and two soil covers (carbonate colluvium and original soil) was measured for two years (Martín-Moreno et al., 2016). This was used to improve the traditional reclamation at this mine by measuring the benefits of properly rescuing original soils and of modifying the linear landforms to concave ones. Concave slopes are an improvement relative to linear slopes (Hancock et al., 2003; Martín-Moreno et al., 2016), but natural concave slopes include a drainage network. Additionally, they are not only concave in 2D, but also in 3D.

GeoFluv – Natural Regrade allowed designing these complex landforms (R4 at Fig. 4), with a drainage network having functional channels ‘stitched’ with convex – concave slopes. The channels of this reclamation project have their headwaters at the toe of the steep highwall descending from the mesa top, from which a small amount of runoff can enter them. The channel dimensions are sized to accommodate that discharge at the headwaters and to increase in the downstream direction to add the additional discharge entering along their reclaimed valley slopes. The two reclaimed channels are classified as Strahler’s first-order streams. The dimensions and 3D shapes of the valley slopes draining to these channels are critical components of this geomorphic design method and we refer to these two small designed catchments within the greater watershed as sub-watersheds.

Fig. 6 shows the two first-order sub-watersheds that were geomorphically reclaimed in two phases using GeoFluv-Natural Regrade, subsequently monitored: in 2012 (2012GF, 0.65 ha) and in 2014 (2014GF, 0.41 ha).

2.2. Geomorphic design and construction using GeoFluv

GeoFluv™ is the trademark name for a specific, patented, landform design method. It uses algorithms based on slope and fluvial geomorphic principles. The essence of this approach is to identify the type of drainage network that would tend to form over a long time at a given location, i.e., to achieve a steady-state landform, considering the site’s earth materials, relief and climate. This is identified at a suitable landscape reference area, in which specific measures (such as drainage density or maximum distance from ridgeline to channel’s head, among others), are made. These are used to design the site (Bugosh, 2000, 2003). The resulting slopes and stream channels are expected to have long-term stability, because they establish a steady-state with the local environment. Natural Regrade is the software that helps users to efficiently make GeoFluv designs in a CAD format.

A GeoFluv-Natural Regrade geomorphic reclamation process includes the following steps: (i) locating stable natural landforms in earth materials similar to those to be reclaimed, within similar environmental conditions of the project area (climate, soils and vegetation), and then measuring their characteristic features (field inputs), (ii) getting a CAD model of the site and setting the design area and its topographic constraints, (iii) making a geomorphic reclamation design following GeoFluv – Natural Regrade and reviewing the design to ensure that it meets the target design criteria and provides correct performance, (iv) exporting the topographic information to guide construction by machine control or for staking-out, (v) building the designed landforms (completed with soils replacement and revegetation), and (vi) monitoring the hydrological and erosive-sedimentary response (Fig. 7).

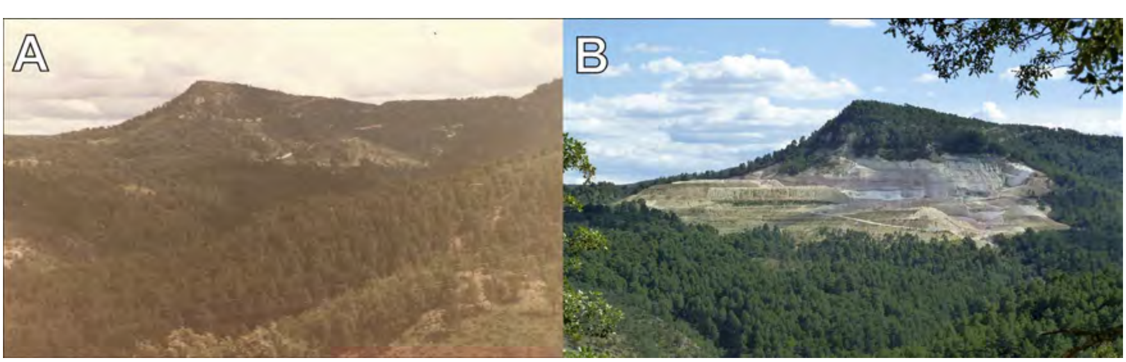

Fig. 3. A) Pre-mine landscape of El Machorro (ADARO, 1983) – a small mesa-type landform, with its slopes and surrounding valleys supporting a pine forest. B) El Machorro mine in 12.09.2013.

Fig. 4. Oblique aerial view of the El Machorro mine in 2014. Photo by Paisajes Españoles (2014). a, open pit; b, un-reclaimed waste dumps; c, ponds; R1, terraces covered with carbonate colluvium; R2, smoothed sloping terraces covered with carbonate colluvium; R3, terraces covered both with carbonate colluvium and soils; R4, geomorphic reclamation using GeoFluv-Natural Regrade (site of this study); ER = experimental mining reclamation waste dump.

2.3. Monitoring the geomorphically-reclaimed area

The geomorphic-based reclaimed area has been monitored to determine its stability and response. This has been carried out by means of diverse methods and for different periods and zones (Table 1) discussed below.

2.3.1. Sediment yield

Sediment yield is the amount of material (eroded and dissolved) that exits a watershed. In most cases is a fraction of the total erosion that occurs within a watershed, because some sediment is internally stored as colluvium or alluvium (Toy and Foster, 1998). Sediment yield in this study has been referred to eroded materials (as the dissolved component has minor geomorphic and hydrologic relevance here) and it has been measured by: (i) quantifying the difference from the total material eroded and deposited within the two first-order sub-watersheds, or (ii) measuring the sediment which passed their outlets towards a pond where they join, by comparing 3D elevation surfaces at the pond before and after sedimentation, and assuming that the volume difference is the sediment derived from the two sub-watersheds (Fig. 8). Topographies were obtained by different methods: direct field measurements (point clouds acquisition) with either TS, differential GPS, TLS and indirect measurements using interpretation (reconstruction) of eroded topographies (Table 2).

The outlet pond, which was dug in natural land (silica sands), was constructed in September 2013. It was monitored in three periods: A) from September 2013 to February 2014, B) from April 2015 to July 2016, and C) from July 2016 to August 2017.

During the first period, the pond was filled with sediments and it was emptied afterwards. During the second and third periods, the pond was not filled with sediment. Therefore, it has not been emptied since February 2014, but there is evidence that during the largest runoff events, water flowed out of the pond. This water must have carried suspended sediment, which was not retained by the pond during those events. Field evidence showed that these spilling events were rare. However, it has to be assumed that the values for these second and third periods are underestimated.

The first (17.09.2013) and last (24.08.2017) surveys of the pond were obtained with Leica's differential GPS 1200 (Table 2). An accuracy of 2.3 cm is assumed for this instrument (Brasington et al., 2003). Four topographies (two from the entire reclaimed area and two of the pond) were obtained as point clouds by using a MS60 MultiStation (Leica), which has both TS and TLS capacities. Before processing these point clouds, each one was cleaned to remove non-ground elements in the

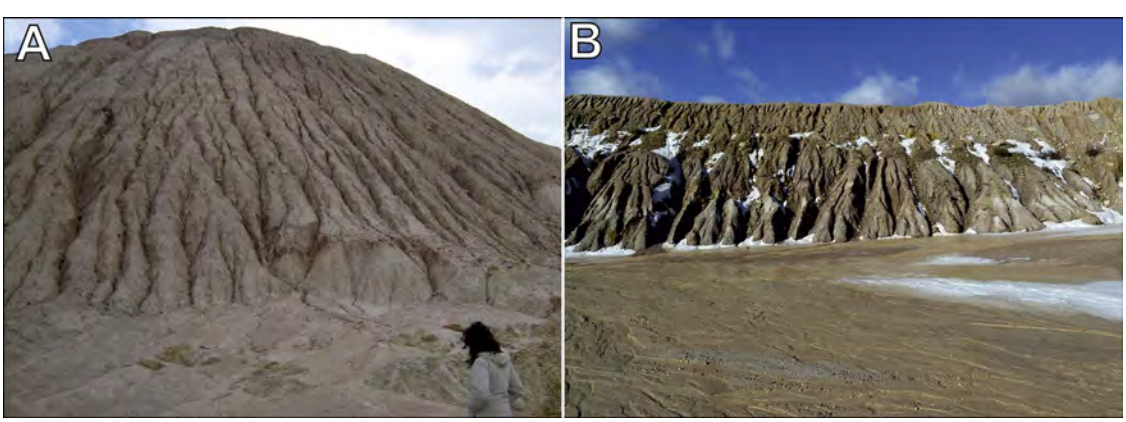

Fig. 5. Erosive-sedimentary landforms of non-reclaimed waste dumps inside the El Machorro mine. A) Rills and associated sand cones. B) Gullies and sand sheets with miniature braided landforms. All the sediments transported from these areas are captured in sediment control ponds (letter c in Fig. 4).

Fig. 6. Oblique aerial view of the El Machorro geomorphic reclamation site. 2012GF was constructed in September 2012 and 2014GF in September 2014. Photo by DGDRONE (2015).

topography, such as vegetation or 'noise', using the LP360 Advanced edition software (Qcoherent software LLC, 2015).

During the 2016 campaign (11.07.2016), some check points were also surveyed – independent points measured with the TS function of the MS60. These were not used to georeference the point clouds, but to calculate the root-mean-square error (RMSE). This accuracy was evaluated with the LP360 control point tool following the American Society for Photogrammetry and Remote Sensing guidelines (ASPRS, 2014). Although the RMSE was calculated only once, every scanning was carried out with the same procedure. The calculated vertical (Z) accuracy of the derived DEM was 3.3 cm and assumed to hold for all others.

The reclaimed surface had a significantly higher vegetation cover for the July 2016 topographical scanning than in April 2015 (see Fig. 9). Therefore, those areas of the point clouds with vegetation clumps were 'cleaned', producing a surface entity with polygons without points (see Fig. 9B.1 and 9-B.2). The cleaned point cloud for July 2016 (Fig. 9B.2) had a lower data density than that of April 2015 (Fig. 9B.3), even though they were surveyed following the same procedure. The reason is that vegetation acted as a 'screen' for the scanning process, making a shadow effect for the point gathering. Hence, we decided to remove those areas with dense vegetation from the analysis, as others have done (e.g., Smith and Vericat, 2015). Using this procedure, we assumed that densely vegetated areas had no significant erosion, and that erosion occurred in areas with little or no vegetation cover. This was confirmed by subjective field evidence (small erosional landforms, such as rills, appeared in areas without vegetation, and vegetated areas lacked any signs of erosion and mass wasting). Rainsplash or sheet-overland flow were possible erosion mechanisms in the vegetated areas, but they were not observed.

The state of the non-eroded September 2012 topography was reconstructed (interpreted) from the April 2015 scanning (slightly eroded topography). The process consisted of an expert interpretation of the contour layout that distinguished non-eroded landforms from eroded ones, following patterns of similar landforms. This process was carried out for the 2012GF area, to complete the set of DEMs to be compared for sediment yield quantifications. This reconstruction was not needed for the 2014GF area, as it was much more stable from the beginning. A similar approach was used in equivalent research situations (Martín-Moreno et al., 2014; Martín Duque et al.,2015) with accurate results. First, a 0.2 m equidistant contour shapefile from the point cloud of April 2015 was derived. The observed erosion between 2012 and 2015 for the 2012GF area occurred mostly as small incision in the main channel, and as subtle rilling in the swales (Fig. 10). Therefore, the contours in those areas were manually smoothed until they reflected the presumed

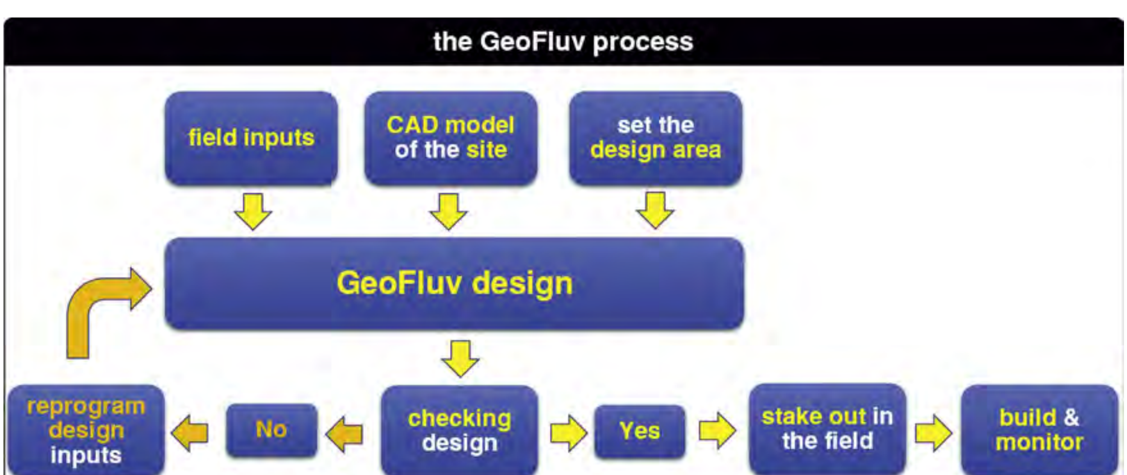

Fig. 7. Diagram showing a GeoFluv procedure. Redrawn from Landforma (2016).

Table 1
Methods and dates of monitoring of the geomorphic-based reclamation at El Machorro mine.

initial date	final date	area	method	target parameter
2012 September	2015 April	2012GF	comparison between one topography scanned and another reconstructed (interpreted)	sediment yield
2015 April	2016 July	2012GF and 2014GF	surface comparison between two scanned topographies of the reclaimed area	
2013 September	2014 February	2012GF	surface comparison between two topographies (surveyed with TLS or differential GPS)	
2015 April	2016 July	2012GF and 2014GF	measuring sediments filling an outlet pond	
2016 July	2017 August			
2014 September	2016 July	2012GF	suspended sediment concentration (SSC) analysis (tubidometry, pressure sensor, H-flume)	suspended sediment load

initial shape (Fig. 10). Because the resultant topography is derived from another one measured by TLS, the same 3.3 cm accuracy was assumed for both. However, it is not possible to define the accuracy of the reconstructed product.

A DEM was derived from each topography. Depending on comparison needs (see Table 1), respective DEM of Differences (DoDs) were obtained by using the Geomorphic Change Detection (GCD) software (GCD, 2015). Specifically, each DoD represents the total net volume eroded or deposited for that period. The GCD software methodology (Wheaton et al., 2010) is based on establishing a minimum level of detection ($_{min}$LoD) defined by the accuracy of each topography. It is assumed that DoD changes below these values cannot be detected and have to be removed from the volume analysis, which was done here. Once the volume was obtained, the mass of sediment (Mg) was calculated by multiplying it by the sediment bulk density ($1.2\ g\ cm^{-3}$), which had been previously calculated for these same materials (see Martín-Moreno et al., 2016) by the core method (Blake, 1965). Additionally, an image of each DoD was obtained, showing the areas where erosion or deposition occurred.

2.3.2. Runoff and suspended sediment concentration (SSC)

A monitoring station was installed to continuously record SSC

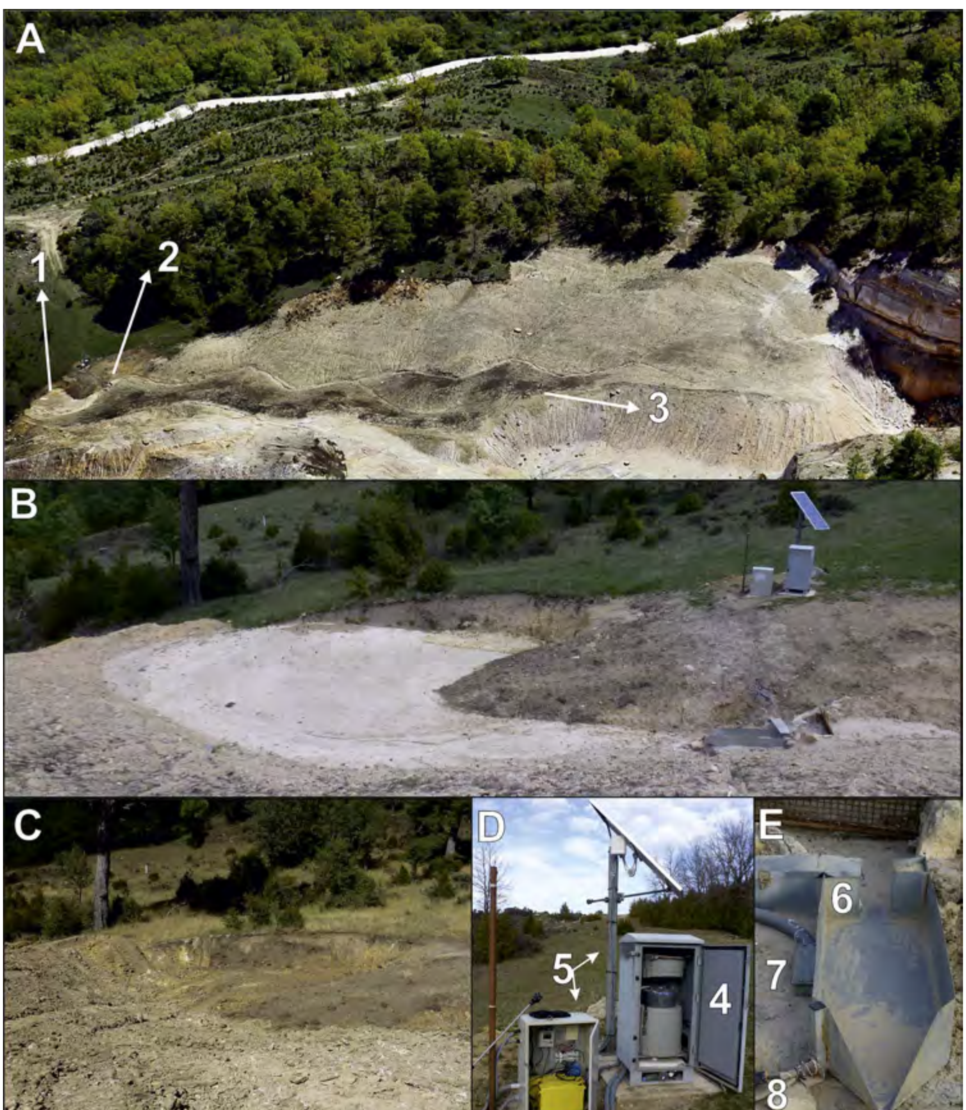

Fig. 8. Sediment yield monitoring at the geomorphic-based reclamation at El Machorro. A is an oblique aerial view of the 2012GF area (1-pond, 2-SSC monitoring station, 3-rain gauge). B is a detailed view of the outlet pond and SSC monitoring station. C is a view of the empty pond in September 2013. D and E are close-up views of the SSC station (4-ISCO sampler, 5-solar panel, batteries, data logger and telemetry, 6-turbidimeter, 7-strainer that took the ISCO samples, 8-pressure sensor, 6, 7 and 8 were installed at the H-flume.

Table 2
Summary of the different methods used to obtain the topographic differences that led to sediment yield quantifications; p, pond; s, surface.

code	area	date	survey method	accuracy (m)
2015p 2016p	outlet pond	2015 April 2016 July	TLS	0.033
2012s	2012GF	2012 September	topographic reconstruction	
2015s 2016s	2012GF and 2014GF	2015 April 2016 July	TLS	
2013p 2017p	outlet pond	2013 September 2017 August	differential GPS	0.023

(Fig. 8) upstream of the outlet pond and downstream of the 2012GF-reclaimed area. This station had:

(i) A 0.229 m H-flume (Teledyne Isco, 2008) through which the runoff passed.
(ii) A 720 Submerged Probe Module from ISCO to measure water depth every 5 min (variations from 1 to 10 min were made until tests demonstrated the best lapse of time). Water discharge (Q) was derived from the records of water depth in the flume. This sensor was also used to obtain a SSC-Discharge (Q) rating curve, which allowed calculation of SSC for periods when the turbidity sensor had no record. This sensor was operational during 01.07.2014–01.04.2016 and was calibrated with 41 samples (SSC in the range 4–45 g l^{-1}) taken by the ISCO sampler. The rating curve is SSC (g l^{-1}) = 7880.5Q ($m^3 s^{-1}$) + 5.7109 (r^2 = 0.6).
(iii) An automatic 24-bottle ISCO 6780 portable sampler. A suction line connecting the ISCO sampler and a strainer inside the flume pumped water and sediments that flowed through the flume. The 720 Module triggered the sampler when water depth attained 5 cm, taking one sample each minute.
(iv) A ViSolid 700 IQ Total Suspended Solids Sensor (0–300 g l^{-1}) connected to an IQ SensorNet 182 controller (both WTW) recorded turbidity each minute. The sensor was calibrated with 6 samples taken by the ISCO sampler through a rating curve (e.g., López-Tarazón et al., 2009). The statistically significant rating curve is SSC (g l^{-1}) = 0.9586*($SSC_{turbidimeter}$ (g l^{-1})) − 0.1008 (r^2 = 0.74). This device was in operation between 04.05.2015 and 01.04.2016.
(v) One tipping-bucket rain recorder (Davis *Rain Collector II*) to measure rainfall.

Until April 2015 the reclaimed area produced a higher-than-expected amount of bedload that covered these instruments. Therefore, a 2 mm mesh sieve was installed upstream of the flume. This sieve retained the bedload, but allowed the finer grained suspended sediments to pass through. After each event, or a series of consecutive events, the sediment trapped by the mesh sieve was collected and deposited in the pond (so that it would appear in the calculated sediment yield value). Simultaneously, the sensors were cleaned and the pressure sensor was recalibrated when needed.

Data from all the sensors were downloaded by means of telemetry with an alarm system, which allowed knowledge in real time when an event was occurring, the amount and intensity of each rainfall event, as well as the number of bottles filled by the ISCO sampler.

3. Results

3.1. Geomorphic reference area and derived design inputs

The reference area was found within the municipality of Peñalén, 3.7 km eastwards of the mine (Fig. 11). It had stable landforms naturally developed on geologic materials similar to those to be reclaimed, shaped also under similar environmental (climate) conditions than those prevailing at El Machorro mine. The geomorphic stability of the area was determined by the absence of landforms denoting active erosion or mass movements (such as rilling, gullying, knickpoints or terracettes).

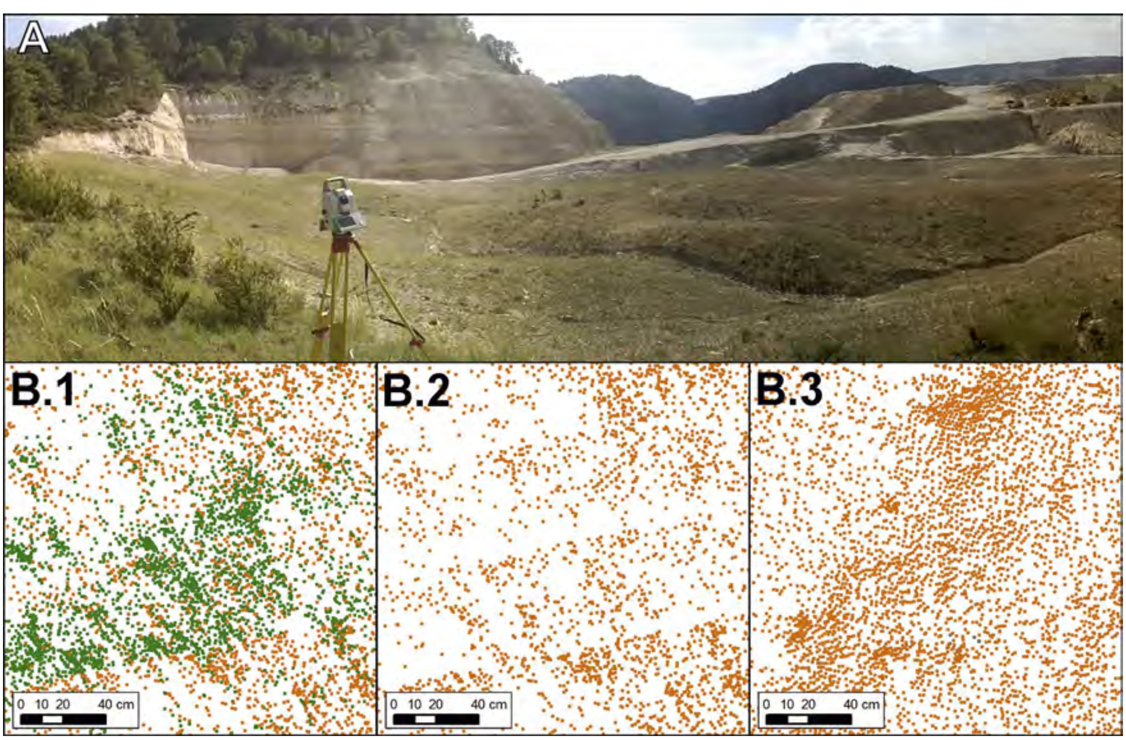

Fig. 9. A) View of the scanned area in July 2016 showing vegetation cover. B) Details of the 'vegetation effect' for topographic comparison. B.1 shows the 2D point cloud of the reclaimed area in July 2016, with all the scanned points (vegetation-green; ground-orange). B.2. shows the situation as of July 2016 only with ground points (after 'cleaning' the vegetation). B.3. shows the situation in April 2015 with all scanned points and the absence of vegetation.

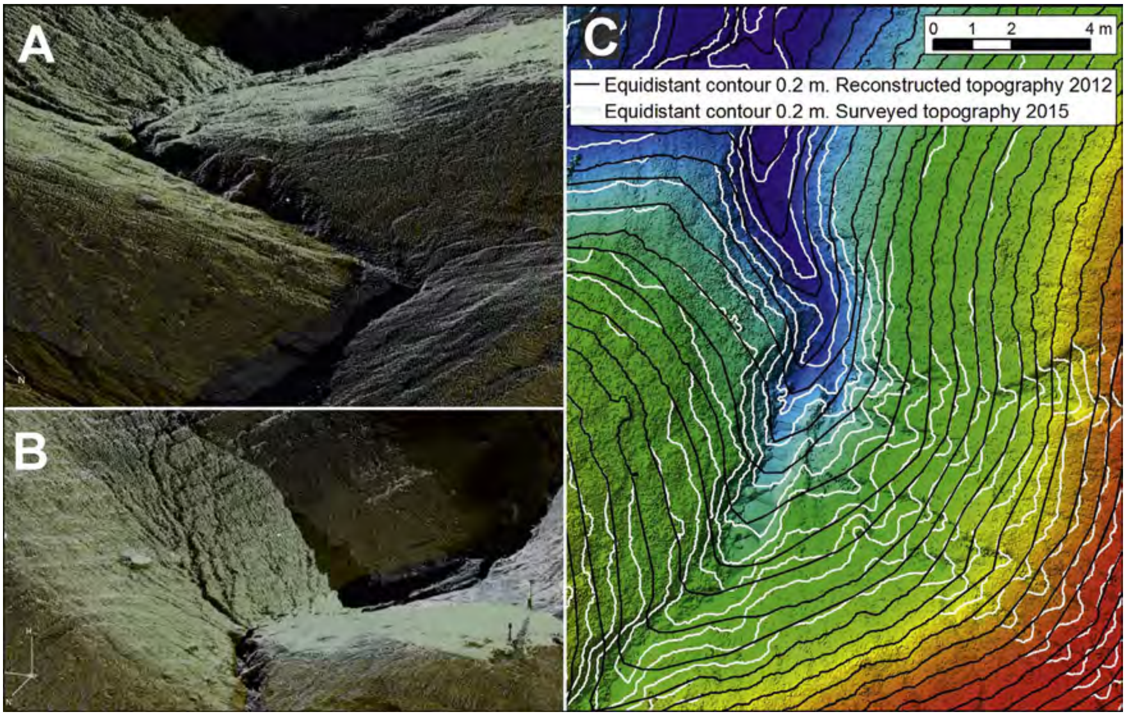

Fig. 10. Details of the erosive landforms appearing in the 2012GF area. A) point cloud view reflecting the incision in the main channel. B) point cloud view reflecting rilling in the swales. C) 0.2 m equidistant contour (in white) from the scanned topography in April 2015 and 0.2 m equidistant contours (in black) reconstructed to simulate the September 2012 topographic conditions. Both contours are shown overlain on a Triangular Irregular Network (TIN) file obtained from the point cloud scanned in April 2015.

GeoFluv – Natural Regrade uses three groups of settings (Table 3). The first is composed by those needed to smoothly integrate the reclamation design to the local topographic conditions at the reclamation site. Two of these settings are the local base level elevation and its slope downstream. In this case, the local base level elevation was that of the outlet pond bottom and the channel's design slope was the slope of the outlet pond bottom. The reason for using these values is that this pond was planned to remain permanently. In this situation, the pond was constructed to provide smooth concave longitudinal profiles to the headwater elevations and slopes; this profile set the design input slope for the channels. The reason for using this approach is that the slope downstream of the pond was too high (11 percent) to start smooth concave profiles upstream that would lie on the upstream ground surface. Channels with an 11 percent mouth slope would result in a headwater elevation that was high above the existing ground surface. A second group corresponds to morphometric parameters of the stable reference area landforms (Fig. 11). Finally, hydrologic information such as rainfall data corresponding to values associated with bankfull and flood prone discharges are needed.

3.2. GeoFluv-Natural Regrade landform design and construction

Fig. 12A shows a 3D view of the GeoFluv – Natural Regrade output design for El Machorro. It imitates the landforms of the natural reference area (see Fig. 11B), with the aim of restoring a similar functionality. It is also adapted to the topographic constraints of this sector of the mine and to the available waste dump volume. The designed landforms consist of: (i) steep "A-channels" with slope between 4 and 10 percent and "Aa+ -channels" with slope greater than 10 percent (Rosgen classification), both having a characteristic zig-zag pattern, sinuosity less than 1.2 and shaped on sand-clay earth material, and (ii) rounded interfluves, the slopes of which have a 'scalloped' topography, composed of sub-watershed ridges and tributary depressions (or swales). Small saddles were also designed along the divides of the main ridges (Fig. 12A).

An excavator and two articulated dump trucks carried out waste mass hauling. A bulldozer accomplished the final regrade of these surfaces. Fig. 12B, C and D show the two main processes involved in this type of topographical regrading: building A-type (zig-zag) channels, and the sub-watershed ridges and swales on the slopes, resulting in a complex convex-concave and scalloped topography.

The geomorphic reclamation was completed with soils replacement and revegetation. Original soils salvaged from active exploitation areas from the same mine were used for reclamation topsoil dressing. The surface was afterwards seeded with a mix of herbaceous and shrubs including *Lolium westerwoldicum, Onobrychis viciifolia, Agropyron cristatum, Agropyron desertorum, Festuca arundinacea, Melilotus officinalis, Piptatherum milliaceum, Retama sphaerocarpa, Lavandula latifolia, Myosotis arvensis, Dorycnium pentaphyllum, Colutea arborescens* and *Genista scorpius. Buxus sempervirens* and *Quercus faginea* were also planted. The vegetation cover was 29 percent at the end of the 2016 summer, in part due to natural dispersion and colonization (Campos, 2016) of the micro-habitats (ecological niches) provided by the geomorphic reclamation's diverse and complex landforms. Specifically, many seedlings of *Pinus nigra* subsp. *salzmannii* and *Genista scorpius* spontaneously colonized the reclaimed surface.

The average slope gradient of the constructed channels is 11 percent. The ridges and swales have average slopes of 31 and 28 percent respectively. The GeoFluv method designs complex slopes that are continually changing in three dimensions to dissipate runoff energy and balance sediment supply with runoff discharge, thereby maintaining a balanced steady-state without accelerated erosion, just as the natural reference area landforms do. Thus, the average slope values may seem high when considered in the context of traditional constant-gradient reclamation landforms. Fig. 13 shows a comparison of the 2012GF area at the beginning (September 2012) and several months after the geomorphic reclamation (May 2014).

3.3. Monitoring the geomorphic reclamation

3.3.1. Sediment yield

The first scanning of the 2012GF and 2014GF areas had a density of

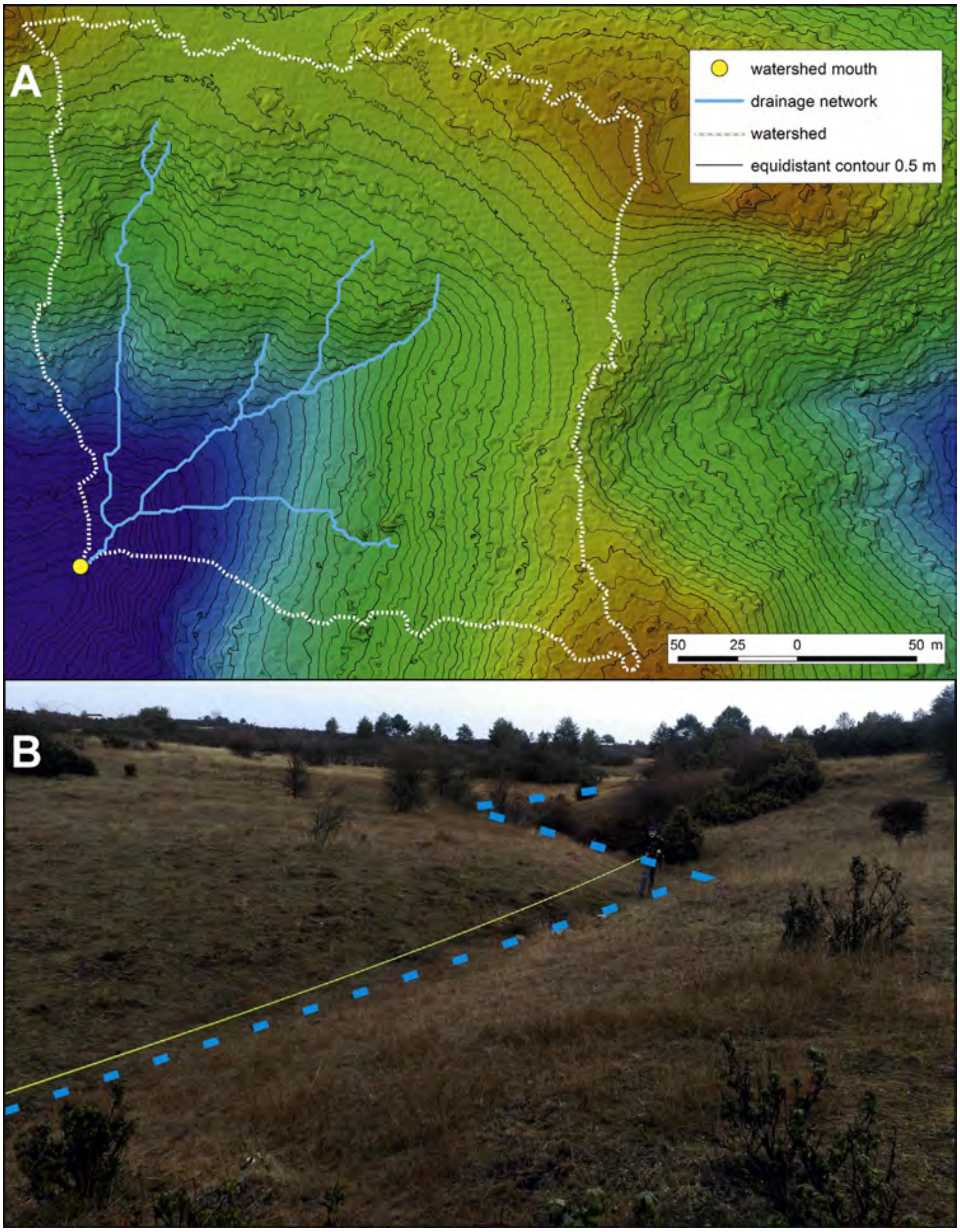

Fig. 11. Reference area used for designing the geomorphic reclamation of El Machorro mine. A) map of one of the watersheds used to obtain inputs, such as drainage density, with the drainage network overlain on a TIN file obtained from LIDAR data of PNOA (2009). B) ground photo of the area, showing measurements of morphometric parameters of channels.

Table 3
Inputs used for the geomorphic design of El Machorro by using GeoFluv-Natural Regrade.

#	input/settings	method and details	value and units
Topographic conditions of the design area			
1	Base level elevation	Pond bottom elevation	1267.0 ma.s.l.
2	Slope at the mouth of the main valleys bottom channels	Pond bottom slope	4%
Morphometric inputs from a stable reference area			
3	'A' channel reach – type of channel with slope > 0.04, according to Rosgen (1994)	Field measurement with tape measure	16.6 m
4	Maximum distance from ridgeline to channel's head	Aerial photo-interpretation, hydrologic analyses through GIS of high resolution DEM and field work check-up	37 m
5	Target drainage density		110 m ha^{-1}
6	Sinuosity of channels with slope > 0.04	Ratio of channel length to the length of the 'A' channel belt axis	1.2
Rainfall and hydrological data			
7	2 yr −1 h rainfall	Intensity-Duration-Frequency (IDF) curves	21.5 mm
8	50 yr − 6 h rainfall		89.2 mm
9	Runoff coefficient	Assigned according to the own experience in similar reclaimed landscapes	0.3
10	Maximum stream velocity	Determined from similar streams in the area	1.37 m s^{-1}

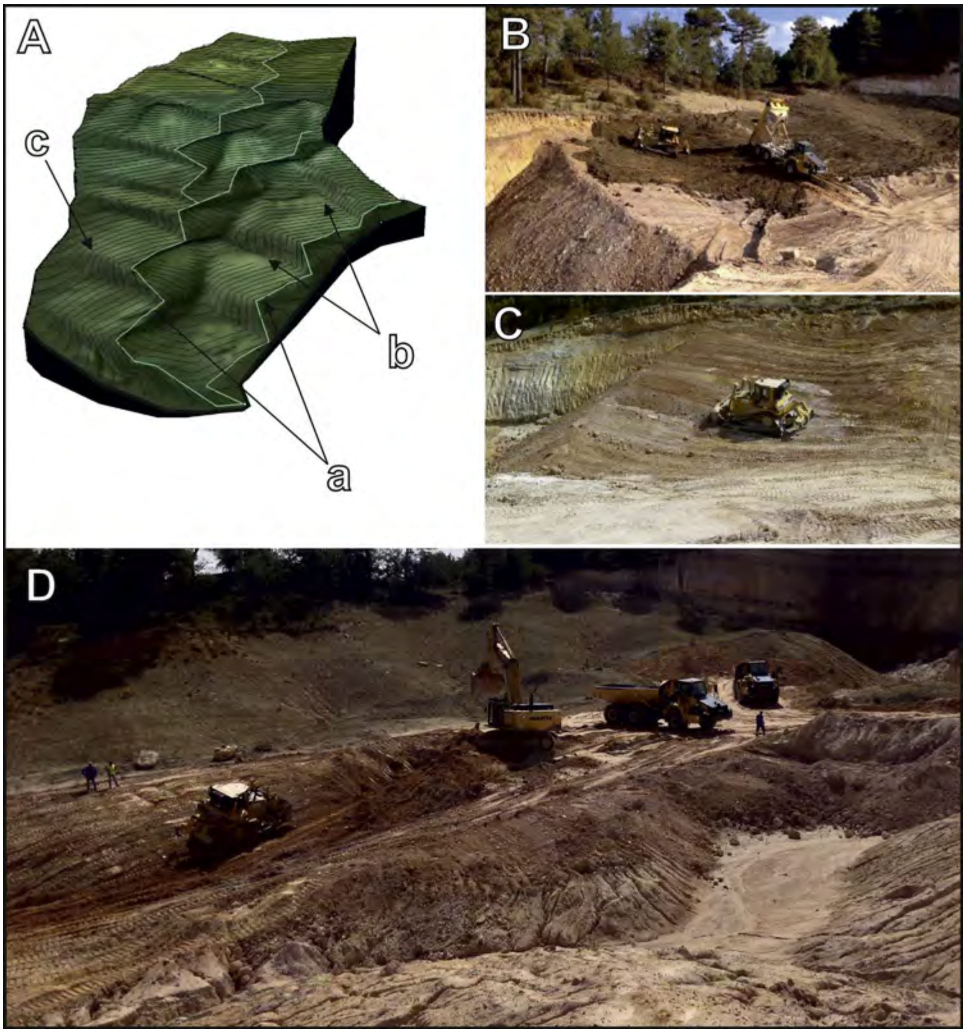

Fig. 12. Details of the geomorphic design and construction at El Machorro. A) 3D view of the geomorphic design. B) Articulated truck and a bulldozer spreading topsoil. C) Bulldozer building a swale. D) Excavator, bulldozer and articulated trucks shaping the main channel at 2014GF area.

684 points/m^2, reduced after the cleaning process to 676 points/m^2. The second scanning had 686 points/m^2, 597 points/m^2 after the cleaning process. Fig. 14B shows our interpretation of the original topography.

Table 4 shows all the sediment yield values estimated from the topographic comparisons, as well as their associated errors. Expressed either as Mg ha^{-1} or as Mg ha^{-1} yr^{-1}, these values show a dramatic decrease of sediment yield with time.

As an example of the compared surfaces, Fig. 15 shows the DoD for the outlet pond between April 2015 and July 2016, with a depocenter of sedimentation of about 1 m.

3.3.2. Runoff, suspended sediment concentration (SSC) and suspended sediment load (SSL)

Altogether 34 runoff events were recorded during the monitoring period. It was not possible to collect data from all the events because of: (i) power outage due to snow covering the solar panel, (ii) pressure sensor covered by sediment, and (iii) temperatures below zero triggered

Fig. 13. Oblique aerial photos of the 2012GF area. A) At the beginning of the geomorphic reclamation, September 2012. B) The site in May 2014. Photos by Paisajes Españoles.

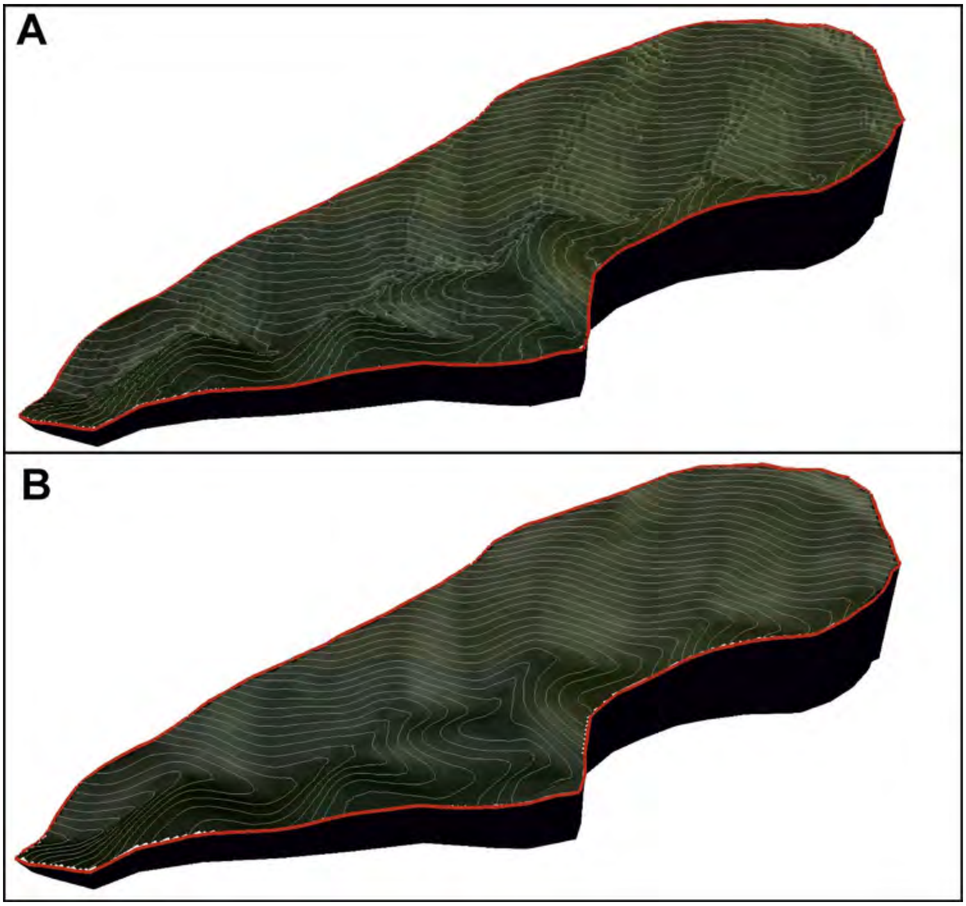

Fig. 14. A) 3D view of the topography scanned in April 2015 for the 2012GF area. B) 3D view of the interpreted topography for the same area immediately after the geomorphic reclamation.

'false' events. Taking into account the Natural Park rangers' field reports and the rain gauge data, it was established that rain intensities greater than 3 mm in 6 h triggered runoff events. There were 32 events above 3 mm/6 h that were not recorded. Accordingly, the total number of events for this period was 66. Hence, 52 percent of the runoff events were collected (34/66 in total, being 12/19 in 2014, 14/30 in 2015 and 8/17 in 2016). The mean discharge was $0.6\,l\,s^{-1}$ and the maximum instantaneous discharge was $18\,l\,s^{-1}$. The latter belongs to event 3 in 2014 (Table 5) having the highest value of SSC and total SSL respectively ($147.6\,g\,l^{-1}$ and 3320 kg). The runoff coefficient was 0.46 during this event. Table 5 also shows the other 6 events that produced higher suspended sediment loads during the monitoring period. The highest runoff coefficient was 0.8 (for event 30) in 2016. However, the corresponding SSC and total SSL values for event 30 were $9.9\,g\,l^{-1}$ and 974 kg.

4. Discussion

The geomorphic reclamation carried out at the El Machorro mine was undertaken in order to determine if it could become an alternative to the widely used traditional gradient terrace and downdrain approach. Evaluating its performance in terms of landform stability and hydrological and erosive-sedimentary dynamics is key for establishing how it performs.

The sediment yield monitoring of the geomorphically reclaimed area was accomplished by using different methods and instruments, and at different time spans, because of adequacy of ground conditions, availability of topographical instrumentation, or contingencies related to the extractive mining activity.

DEM comparisons of the sediment pond and between ground surfaces reflect that the initial sediment yields from the 2012GF area were

Table 4
Sediment yield values obtained for the geomorphically reclaimed surface at El Machorro.

period		source area	sediment yield				rainfall
start	finish		total	error (+/−)	annual	error (+/−)	mm
			Mg ha^{-1}		Mg ha^{-1} yr^{-1}		
direct DEM comparison at sediment pond							
17.09.2013	13.02.2014	2012GF	95.3	7	–	–	340
08.04.2015	11.07.2016	2012GF and 2014GF	23	3.6	18.4	3	813
11.07.2016	24.08.2017	2012GF and 2014GF	4.35	2.1	4.02	1.9	514
DEM comparison between surveyed and reconstructed (initial) surface							
17.09.2012	08.04.2015	2012GF	184	74	71	28	1384
DEM comparison of the reclaimed surface							
08.04.2015	11.07.2016	2012GF	25.2	21.6	20.2	17.3	813
08.04.2015	11.07.2016	2014GF	19.7	20.7	15.8	16.6	813

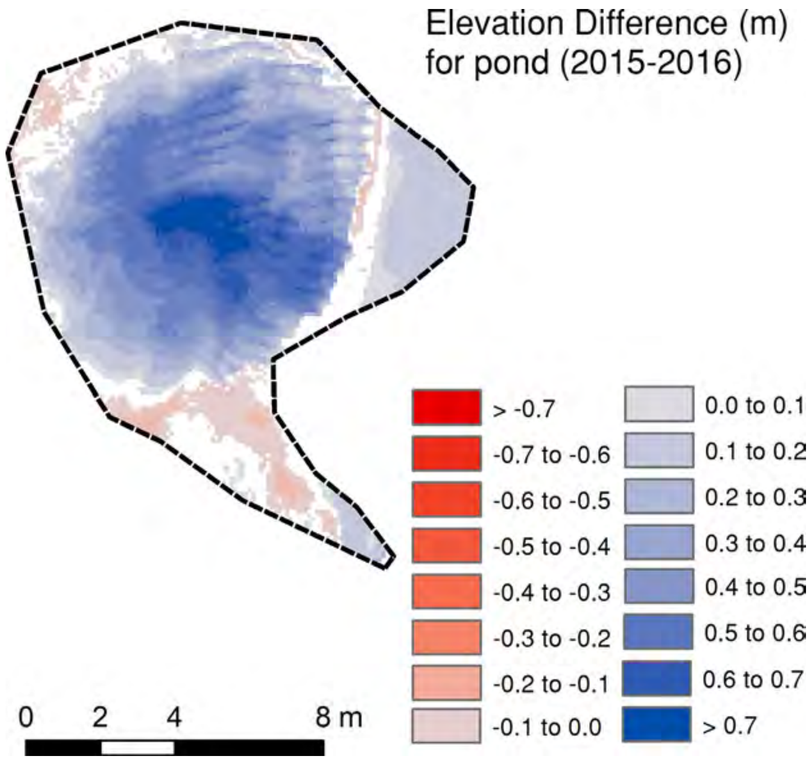

Fig. 15. DoD for the pond located at the outlet of the geomorphic reclamation of El Machorro, for the period April 2015 – July 2016.

higher than expected. A field inspection confirmed rilling in the swales and incision of the main channel up to 08.04.2015.

Our interpretation of these erosive changes are: (i) the local base level of the 2012GF reclaimed area (elevation and slope of the outlet pond) was not accurately constructed as it was designed, so that this area underwent geomorphic adjustments, mostly in the form of decimeter incision of main channel (but also as subsequent centimeter swale rilling, as the base level of the main channel lowered), and (ii) the vegetation did not grow properly during the first two years for unknown reasons. Indeed, a 30 percent vegetation cover – one that was not attained at that time – can significantly reduce erosion of reclaimed mined areas (Moreno-de las Heras et al., 2009). The 2014GF area was properly connected to the base level, and did not undergo erosive adjustments.

The results obtained after April 2015 from direct topographic comparisons of the pond can be considered as: (i) low erosion rates from April 2015 to July 2016 (18.4 Mg ha^{-1} yr^{-1}) and very low from July 2016 to August 2017 (4.02 Mg ha^{-1} yr^{-1}), (ii) reliable data, as obtained from direct field measurements, despite of the fact that the pond did not retained the finest sediment fraction for a few events, and (iii) representative of the sediment yield of the entire reclaimed area (2012GF + 2014GF).

The comparison of scanned surfaces of the sub-watersheds introduced uncertainty due to the following reasons:

(i) Among all the calculated errors, these scanned topographies have the highest uncertainty (almost 100 percent), because the changes detected are only slightly higher than the minimum detection limit. GCD through DoDs is recommended where the geomorphic changes are considerably larger than the minimum detection limits (Wheaton et al., 2010). In our study, this condition existed for DoDs in the pond.

(ii) Sediment yields obtained by DoD for the reclaimed area can be affected not only by erosion/deposition, but also by shrinking/swelling effects. This influence has been noticed and quantified in sub-humid badland areas (Vericat et al., 2014) and in coal mines located in the Iberian Range (Teruel coalfield), near the Alto Tajo (Nicolau, 2002). The El Machorro reclaimed area may have had some shrinking (settling), as this is a common process in mining areas (CMSA, 2007). In this case, the surface underneath the geomorphic reclamation was undisturbed, and loose sediment (mining wastes) were placed upon it, so that the loose materials likely settled with time.

Because the aforementioned two factors (high errors and shrinking effect) did not affect the changes detected in the pond, we consider that

Table 5
Water discharge and suspended sediment concentration (SSC) and load (SSL) for the six events with the highest values between 01.07.2014 and 01.04.2016. Runoff depth is expressed as total discharge for event divided by the surface area, thereby quantifying the runoff coefficient, expressed as well as percent of rainfall depth.

event	date	Q_{mean}	Q_{peak}	runoff depth	rainfall depth	runoff coefficient	SSC mean	SSCmax	total SSL
		$l\ s^{-1}$		mm			$g\ l^{-1}$		kg
1	02.07.2014	1	4	2.6	16.4	0.16	14.3	36.1	403
3	31.08.2014	2	18	9.3	20.1	0.46	19.2	147.6	3320
12	14.12.2014	0.1	5	11.4	23.4	0.49	12.9	42.1	1170
25	02.11.2015	0.4	6	5.1	29.9	0.17	10.8	50.5	695
28	03.01.2016	1	10	7.2	45.5	0.16	7.4	17.3	398
30	09.01.2016	1	3	18.4	23	0.8	7.9	9.9	974
31	10.01.2016	4	10	16.1	36.5	0.44	7.1	9.5	688

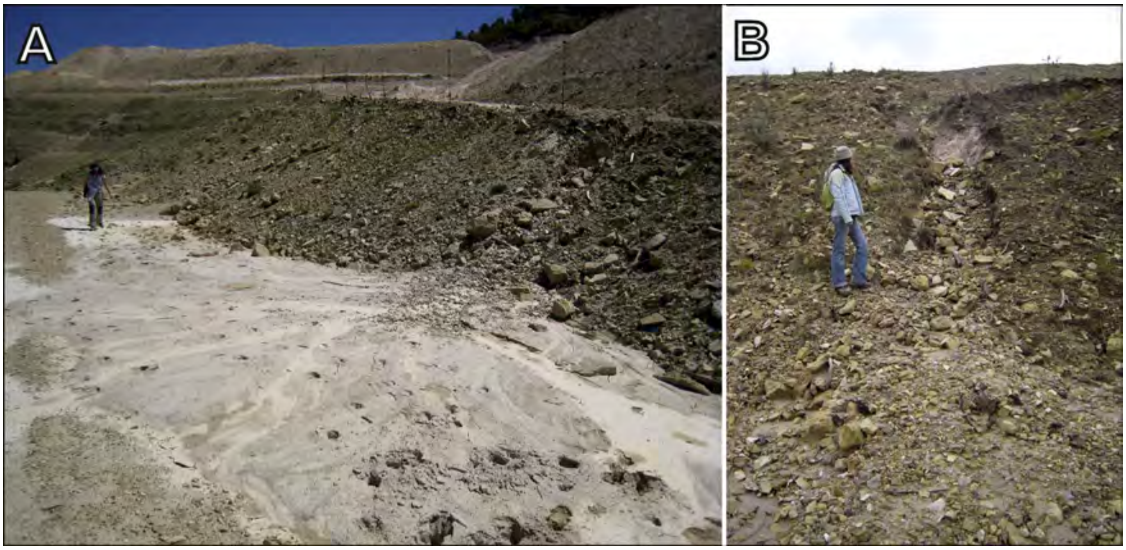

Fig. 16. A and B, two situations of gradient-terraced reclamation landforms at El Machorro affected by gullying processes caused by run-on entering from internal (hauling) roads.

the pond values are more reliable than those obtained from comparison of scans, although the latter, with their uncertainties, generated similar sediment yield values, which confirm that the possible settling effects was minor in the reclaimed area.

The situation discussed above portrays a significant sediment yield decrease from the geomorphically reclaimed area after April 2015. Erosion before that date is interpreted as adjustments to grading errors due to construction of the design, reinforcing the assumption that had the design been accurately built, the initial sediment yield values would have been much lower.

A closer analysis of results shows that erosion between September 2012 to April 2015, 71 Mg ha^{-1} yr^{-1}, can be attributed to channel incision (55%) and swale rilling (45%). The erosion between April 2015 and July 2016, 18.4 Mg ha^{-1} yr^{-1}, is attributed to attenuated channel incision and minor swale rilling. Finally, from July 2016 to August 2017, a low erosion in the reclaimed area (4.02 Mg ha^{-1} yr^{-1}) was confirmed by no further channel incision nor swale rilling during this period. This evidence supports our conclusion that erosion was initially triggered by grading errors. This emphasizes the importance of proper, specified tolerance construction. With minor deviations, as in this case, flowing water quickly 'adjusts' construction irregularities through the processes of erosion and sedimentation. This highlights the need to agree on construction tolerances and on the understanding of the equipment operators of where the most 'sensitive' areas are (e.g., dimensions of channel bottom are more critical than ridgeline elevations). Just as natural sub-watersheds include sediment storage areas, the freshly graded reclamation surface will have both high and low spots within the construction tolerances, and during initial storms, sediment is moved from high spots to low spots. In this case, because the area is small, sediment moved from the reclaimed area to the pond. However, after initial adjustments occurred, the reclamation surface was more reflective of the design and the resulting surface remained 'stable'. Because it is not practical to hold extremely tight tolerances when constructing with heavy earth moving equipment typically used in surface mining, it is advisable to construct sediment traps at the mouth of the sub-watersheds, so that any sediment from erosion of grading irregularities does not leave the site. Those sediment traps can be permanent (as this one, built to provide a smooth concave longitudinal profile to the headwater elevation), or temporary. In the latter case, once inspection of the sub-watershed shows that grading irregularities have been adjusted and acceptable stability has been achieved, the temporary sediment traps can be breached and runoff can flow freely with confidence that it will have acceptably low sediment yield.

The 4.02 Mg ha^{-1} yr^{-1} sediment yield value for the July 2016-August 2017 period is:

- in the lower range compared to those measured at this same mine at the slope plot-study scale (concave slope with topsoil), during 2008–2010 (3–20 Mg ha^{-1} yr^{-1}, Martín-Moreno et al., 2016);
- much lower that the sediment yield that occur at un-reclaimed areas within the same El Machorro mine 292 Mg ha^{-1} yr^{-1} (Martín-Moreno, 2013) – measured quantifying the sediment that it is stored at the sediment control ponds within the mine (see Fig. 4);

The most comparable study (in terms of geomorphic reclamation approach and watershed scale) is a sediment yield monitoring carried out on GeoFluv-Natural Regrade reclamation at the La Plata mine, in the semi-arid environment of New Mexico, United States (Bugosh and Epp, 2015). The values reported are 9.53 Mg ha^{-1} yr^{-1} for an undisturbed native site, 8.25 Mg ha^{-1} yr^{-1} for a GeoFluv-Natural Regrade reclamation with topdressing and poorly established vegetation, and 5.65 Mg ha^{-1} yr^{-1} for a GeoFluv-Natural Regrade reclamation with topdressing and significant vegetation establishment. However, caution is needed when comparing that site's sediment yield values to El Machorro's, because the physiographic conditions are different.

Visual comparisons for the 2012–2017 period between the geomorphic reclamation and the traditional gradient terrace and down-drain reclamation of El Machorro show that the geomorphic reclamation underwent, at most and only until April 2015, decimeter incision of the main channel and centimeter rilling in swales, with neither rilling nor incision continuing once the base level stabilized and vegetation grew. In contrast, adjacent terraces at El Machorro recurrently broke by gullying processes, with incisions deeper than one meter in most of the cases, demonstrating that they are an unstable reclamation landform even during the period that mining is active, as well as in the long term (Figs. 16 and 17).

The observed reasons for gullying of terrace-constructed landforms of El Machorro are either run-on from hauling roads (Fig. 16) or slope inversion because of sediment accumulation in the internal part of the berm (Fig. 17). Once run-on happens, it discharges concentrated flows from across the terrace bench onto the outslopes and initiates gullying. When these effects occur, Caobar immediately proceeds to correct them, but they require very costly interventions.

Runoff and suspended sediment monitoring had the complications described at the *Results* section. In addition, the number of samples used to calibrate the turbidity sensor was small. From this situation, water

Fig. 17. Inversion of a berm slope by sediment accumulation at the toe of the upper outslope, leading to gullying downstream.

stage should be monitored by non-contact radar gauging, to avoid such problems.

Calculated runoff coefficients ranged from less than 0.16 up to 0.8 (Table 5). The key factors causing this variation appear to be the antecedent conditions of the soils due to previous rain events, as well as seasonal variations (Latron et al., 2008; Estrany et al., 2010; López-Tarazón and Estrany, 2017), but the large number of missed events impeded a full understanding of the variations. Despite reporting only some of the relevant information that could affect SSC, they definitely decrease temporally (Table 5). Indeed, events 1, 3 and 12 delivered high loads of sediment. By comparison, although equivalent rainfall depths were recorded at the end of 2015 and at the beginning of 2016, events 25, 28, 30 and 31 yielded much lower suspended sediment loads than in 2014.

5. Conclusions

A complete process of geomorphic reclamation (GeoFluv method), from designing to building to monitoring, was carried out at El Machorro mine from 2012 to 2017. A suitable and stable landscape reference area was found nearby, from which the corresponding inputs were measured to make a CAD using Natural Regrade for two first-order stream watersheds. This design was thereafter constructed, although with inaccuracies at the base level elevation and slope affecting one sub-watershed (2012GF). Subsequent monitoring of sediment yield, runoff and SSC was carried out, spanning five years in total. It is considered that this process of geomorphic reclamation, from finding suitable stable reference landforms to the monitoring process, in addition to the design and construction phases, is in itself a contribution, because: (i) there are not many examples of geomorphic-based reclamations worldwide yet, (ii) there are very few monitoring processes of mine rehabilitation at a watershed scale, and (iii) only one similar situation (La Plata, New Mexico, US) has been found.

The sediment yield values obtained from September 2012 to April 2015 at the 2012GF area were higher than expected, with incision of the main channel and rilling in the swales. These erosive adjustments are interpreted as the result of: (i) the local base level not being properly fixed (mostly), and (ii) vegetation growth that did not occur initially (less critical).

Once the local base level underwent the needed adjustment, and vegetation cover exceeded about 30 percent, sediment yield reached 18.4 Mg ha^{-1} yr^{-1} from April 2015 to July 2016 and decreased to 4.02 Mg ha^{-1} yr^{-1} from July 2016 to August 2017. These values can be considered reliable and representative for this reclamation method at this site because: (i) they were obtained from direct sediment quantifications of the filling of the outlet pond, and (ii) they are the outcome values of two entire sub-watersheds, rather than from a single plot or slope, being more representative of what a reclaimed mined site yields as a whole.

Further research is needed to establish a more conclusive evaluation of the sediment yield obtained from this geomorphic reclamation, to evaluate its performance during a much longer period of time, and also to compare its sediment yields to those from: (i) terraced-downdrain reclamation landforms; and (ii) from physiographical equivalent natural areas (baseline).

In any case, sediment yield values from April 2015 show that geomorphic processes operate within the reclaimed area at very low rates, with no on-site or off-site degradation of the environment. This means that in a critically vulnerable area to erosion, such as the Alto Tajo, geomorphically reclaimed areas like this one can even be hydrologically connected with the natural fluvial system.

This study shows that even when construction-grading errors were present at the 2012 GF area, the site stabilized to background (acceptable) conditions within two-and a half calendar years (three growing seasons). Additionally, our observations of the area without grading errors (2014GF area) strongly suggests that the final low sediment yield, steady-state equilibrium would be obtained very quickly following proper construction (a few months, a growing season).

Although the described geomorphic reclamation is a relatively small demonstration project, it is concluded, from its feasibility and results so far, that it constitutes a new, real, solution for mining reclamation for the highly landscape-ecologically sensitive Alto Tajo area, with potential to be used in most open pit mines.

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