C. Monitoring of the Impact of the Project actions. Action C 1.1 Monitoring of topographic evolution and erosion rate

LIFE16 ENV/ES/000159

[José Manuel Nicolau, Escuela Politécnica Superior. Universidad de Zaragoza]
[nicolau@unizar.es]

[Andrea García García] [andgarciagarcia@gmail.com]

[Cristina Martín Moreno, Facultad de Geología. Universidad Complutense de Madrid] [crismartin@geo.ucm.es]

[José Francisco Martín Duque, Facultad de Geología. Universidad Complutense de Madrid]
[josefco@ucm.es]
[María Tejedor Palomino, Facultad de Geología. Universidad Complutense de Madrid]
[mariatejedor@ucm.es]

February 2022

☐ External ☐ Informative ☐ Technical ☐ Others

☐ Internal ☒ Monitoring ☐ Financial

This project has been funded with support from the European Commission.
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CONTENT

ABSTRACT

Erosion in restored mining areas is one of the most important constraints to the success of restorations. Numerous conventional restorations based on a slope-berm-ditch topography and with inadequate substrates develop networks of rills and gullies that limit the development of soil and vegetation (on site effects). In addition, if these eroded materials are released into natural channels, severe impacts can be produced on aquatic ecosystems (off site effects). The Tecmine restoration in Fortuna quarry has applied Geomorphological Restoration as an alternative to conventional restoration to reduce the intensity of erosion and make it compatible with the development of vegetation and soil as well as to reduce the hydrological impact.

The evaluation of rill networks is the best indicator of the ecological effects of erosion in restored mining areas. In Tecmine project a methodology based on Digital Elevation Model (DEM) obtained from photographs taken with drones has been applied. However, vegetation growth in the second year produced distortions in the DEMs, making this methodology unfeasible until it is possible to use lidar technology in drones. Therefore, in 2021, rill measurements were taken in the field on a representative sample of the restoration as a whole. Rills density (m/m^2) is the most direct and reliable indicator among others used.

Two findings must be considered in order to properly assess the erosion data recorded in restored mining ecosystems. First, according to Hancock et al (2016) there is an initial high pulse of sediment over the first three years, which rapidly reduces to rates similar to that expected for a natural or undisturbed surface. Second, rill density about 0.60-0.70 m/m^2 is considered a threshold value that sets the success of the plant community development. Above that value erosion prevents vegetation development in restored mining areas very similar to Fortuna quarry (Moreno de las Heras et al, 2009; 2011).

Results show that the canonical geomorphological restorations (GeoFluv) - where it has been possible to build a smooth topography and place a colluvium substrate - are very little erosive. This implies, on the one hand, that they present favourable conditions for the development of plant communities and, on the other hand, that they emit little sediment to the natural drainage network. Indeed, in the eastern restoration zone ("Small GeoFluv") the formation of rills has been practically null. The western ("Big GeoFluv") canonical GeoFluv restorations has developed few rills (0.15 m/m2). However, in areas where canonical geomorphological restoration could not be applied -mainly due to lack of space- the density of rills is close to the threshold value. The absence of colluvium type substrate also favours the formation of runoff, although in values within the tolerance range.

With respect to the constructed watercourses, upward erosion is being moderate and compatible with the ecosystem stability in canonical GeoFluv restorations. It affects 30.5% of the length of the western restoration channel ("Big GeoFluv"); and between 49 and 58% of the length of the eastern GeoFluv channels ("Small GeoFluv"). It is expected that upstream erosion will continue to progress towards the upper reaches of the streams. In the Abrupt Geomorphological Restoration area, the upstream erosion in the main channel is really important, affecting 77.4% of the length of the channel. It is advisable to carry out a follow-up of this watercourse in the coming years, as an afterlife activity.

INTRODUCTION

Undoubtedly, the phenomenon that most limits the success of restorations in more parts of the world is the erosive effect of runoff. There are numerous examples of failed restorations due to the erosive action of runoff, which conditions the development of the soil and vegetation.

Water erosion in mining restorations is mainly caused by the construction of inadequate geomorphologies (topography and substrate). The “dump heap” type topography, also known as the “slope-berm-ditch model” is very widespread (Nicolau, 2003). These are reliefs with more or less steep rectilinear slopes, stepped in berms (terraces) and with a drainage network made up of ditches to evacuate the water generated on the slopes and collected in the berms. This artificial drainage system has been shown to be non-functional in evacuating runoff from the most intense rainfall events. The water is often retained in the berms, causing them to break and the formation of gullies on the slopes. On the other hand, the slopes -without a drainage network- can experience processes of sheet erosion and rills network development, even with some gullies. These are favored by a very frequent circumstance in these mining topographies: the entry of exogenous runoff through the head of the slopes, which advises maximum control over them in restoration projects (Hancock et al., 2003). The negative effects of the topography are accentuated when the restored substrates have a low rainwater infiltration capacity and/or have a high erodibility. Figure 1 shows an example of this type of restoration.

What are the ecological effects of erosion on mining slopes? When networks of rills and gullies are formed, the establishment of vegetation inside them is limited by their instability. And outside of them -in the interills areas- it has been identified that, rather than reducing the chemical fertility of the soil or eliminating seeds, erosion affects the development of the soil and vegetation by causing a decrease in soil moisture content. This occurs because the rills give rise to an efficient evacuation of the runoff, which leaves the slopes in pluvial events (Moreno de las Heras et al, 2010). This intensification of the water deficit caused by erosion in rills notably conditions plant colonization and soil development. Specifically, it has been proven that it limits seed germination, survival and seed production of plants and it has been seen that it reduces primary production and species richness in a negative exponential way (Espigares et al 2011).

Thus, the two abiotic factors that most limit the success of Mediterranean mining restorations are water erosion and the availability of water for plants. For this reason, action C1 of the monitoring of the Life Tecmine project consists of 2 sub-actions: C1.1 Monitoring of topographic evolution and erosion rate and C1.2 Monitoring of water flows and sedimentation

Figure 1. Rill and gully formation on a steep long restored outslope and berms. Observe the propagation of gullies to the higher parts of the slope. It is also possible to see the lack of soil and the poor performance of the pine trees and some shrubs plantation.

SCOPE OF THE DOCUMENT

This document shows the results of the C1.1 sub-action: Monitoring of topographic evolution and erosion rates. In essence, this document intends to analyse if the erosion rates recorded in the restored areas of the quarry can compromise the development of the vegetation.

STRUCTURE OF THE DOCUMENT

The deliverable presents a classic structure of introduction, methodology, results and discussion.

The introduction explains the importance of erosion monitoring in the evaluation of the success of mine restoration. This is followed by the baseline with its own methodology. The methodology section explains the set of measurements that have been carried out. The results are summarised in 3 figures and a table. Finally, the discussion presents the context for interpreting the results.

An annex has been added to explain and justify the changes that were agreed with the Commission's evaluators.

GENERAL AND SPECIFIC OBJECTIVES OF THE ACTION

This action has focused on the study of the topography evolution, estimating the soil erosion rates (sediment yield). The effectiveness of the GeoFluv restoration method with that of the conventional restoration methods is compared. This information will allow, on the one hand, to evaluate the limitations of erosion on the development of vegetation (on site effects) and, on the other hand, to estimate the sediment yield (off site effects).

The specific objectives of the action “C1.1 Monitoring of topographic evolution and erosion rate” have focused on evaluating the effect of various factors and restoration scenarios on erosion (density and volume of rills; and rate of erosion). The factors and scenarios considered have been the following:

- Baseline (dump closed to the restored area)

- Geomorphological restoration in the strict / canonical sense

- Geomorphological restoration with overburden substrate

- Geomorphological restoration with abrupt topography

- Evolution of the constructed watercourses in terms of upward erosion

In the initial Tecmine project proposal, it was planned to carry out measurements of suspended solids in natural channels to quantify the emission/inmission of sediments. However, these measurements were replaced by the quantification of the density of rills and the quantification of the sediment yield. Annex 1 shows the request from the University of Zaragoza for this change and the response from the European Commission.

DESCRIPTION OF THE BASELINE

Introduction

As a baseline of the Tecmine restoration, the previous state of the quarry has not been taken, since it was a landscape of mining holes, tailings, waste substrate, inadequate to support a functional ecosystem. A conventional restoration of a space adjacent to the one that has been restored in the Tecmine project has been taken. Figure 2 shows a picture of the conventional restoration used as baseline. Conventional restoration consists of a topography of slopes and berms with drainage ditches, on which substrates of different nature are spread and herbaceous plants are planted to control erosion and a subsequent planting with pine species. That would have been the restoration that would have been carried out if the Tecmine project had not been developed. Therefore, it is taken as a reference in order to check the effectiveness of the Tecmine restoration compared to the conventional one.

Figure 2. Fragment of the PNOA aerial orthophoto showing (approximately) the platform area that will be restored within the TECMINE project (green line) and the conventionally restored terraces where erosion has been measured (red line) (Coordinate System UTM-30N, Datum ETRS 1989).

Methodology

Two type of indicators have been used: a) Rill and gully density; b) Annual total erosion by rilling and gulling processes

According to the LIFE Performance Indicators table, the selected indicators should be included in the objective *Sustainable land use, agriculture and forestry* → *Soil/Land indicators* and in the objective *Improved Environmental and Climate Performance (including resilience to climate change)* → *Water*, as shown in Table 1.

Table 1. Selected erosion indicators (from Life permormance indicators table)

Objective	**Indicators**		**Units**
Erosion indicators			
Sustainable land use, agriculture and forestry	Soil / Land	Soil Surface improved by GeoFluv	ha
		Rill and gully density	**m/m^2**
		Annual total erosion by rilling and gulling	**Mg/ha/yr**
		Maximum peak flow (Q_p)	m^3/s
		Volume of improved water	m^3

To measure rills and gullies density on the conventionally restored spoil heap, the detailed orthophoto obtained by photogrammetry (drone flight made on June 2018) and ArcGIS software have been used.

First of all, the surface occupied by the two types of spoil heap was delimitated (red line in Figure 3). They are characterized by:

- Type 1: long, steep outslope with narrow berms
- Type 2: small, steep outslope with wide berms

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Figure 3. Fragment of the PNOA aerial orthophoto showing the two types of conventionally restored terraces, where erosion has been measured (Coordinate System UTM-30N, Datum ETRS 1989)

After delimitating both spoil heaps areas, rills and gullies observable in the orthophoto were drawn (see Figure 4).

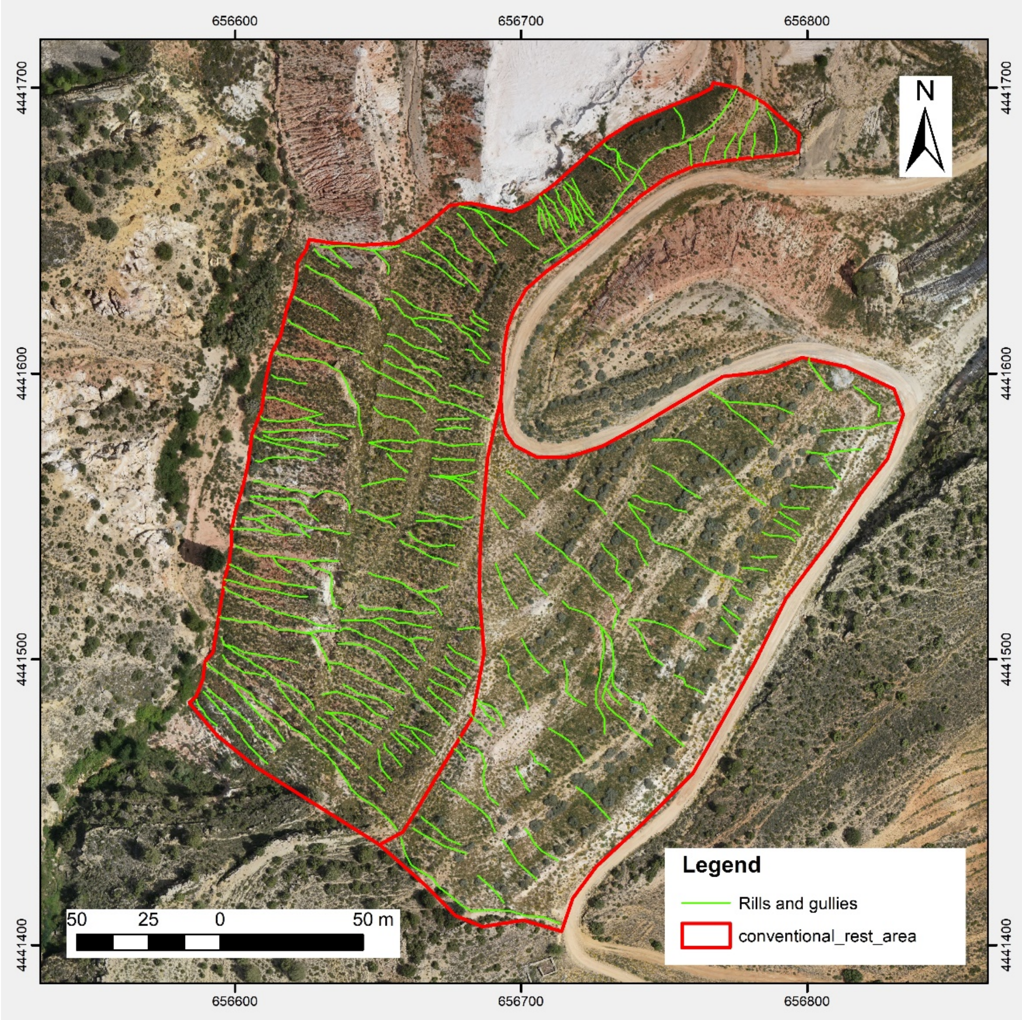

Figure 4. Fragment of the detailed orthophoto with the rills and gullies identified (Coordinate System UTM-30N, Datum ETRS 1989).

Once all appreciable rills and gullies were drawn (Figure 3), the sum of rills and gullies length (in m) was calculated, and this was related to the surface (in m^2) occupied by each spoil heap type (red line in figures 1, 2 and 3). By this way, rill and gully density was calculated in terms of m/m^2.

To estimate annual total erosion by rilling and gulling processes at the two types of spoil heap, we first built a triangulated irregular network (TIN) representing the detailed topography of the eroded spoil heaps (current situation, 2018-TIN). To build this TIN, we used the detailed topography obtained by the drone flight made on June 2018 and the ArcGIS software. From this 2018-TIN, 1-m contours were generated, and the area occupied by each spoil heap was delineated. Then, we erased the contours within the gullies, leaving only the parts representing the 'original surface', it is to say, areas that neither have undergo rilling, nor gulling erosion. Next, the contours of the original terraces were edited to reconstruct the original terraced topography (linear outslopes, which were built in 2006). Following that, we built another TIN representing the terraced topography without gullies (original situation, 2006-TIN).

Finally, both TINs, the original reconstructed terraced, 2006-TIN, and the one representing a recent situation with rills and gullies, 2018-TIN, were compared (subtracted) by using the ArcGIS ‘surface difference’ tool (Figures 5 and 6). By comparing both TINs, we obtained the difference volume (m^3) between them. The mass of eroded waste (in Megagrams) was calculated by multiplying the volume (in m^3) by the waste bulk density. The bulk density value used was 1.54 g cm^{-3}, calculated by the UCM group for very similar materials (Martín-Moreno et al, 2018). We also measured the projected area of each waste dump by using the orthophoto taken by the drone, with the ArcGIS software.

The mean annual total erosion (equivalent here to sediment yield, since no sedimentation occurs within the rills and gullies) for both spoil heap, in terms of Mg/ha/yr, was calculated by dividing the mass of waste (in Megagrams) by the area of each spoil heap (in hectares) and the 12-year time span in which the recorded erosion took place (2006–2018).

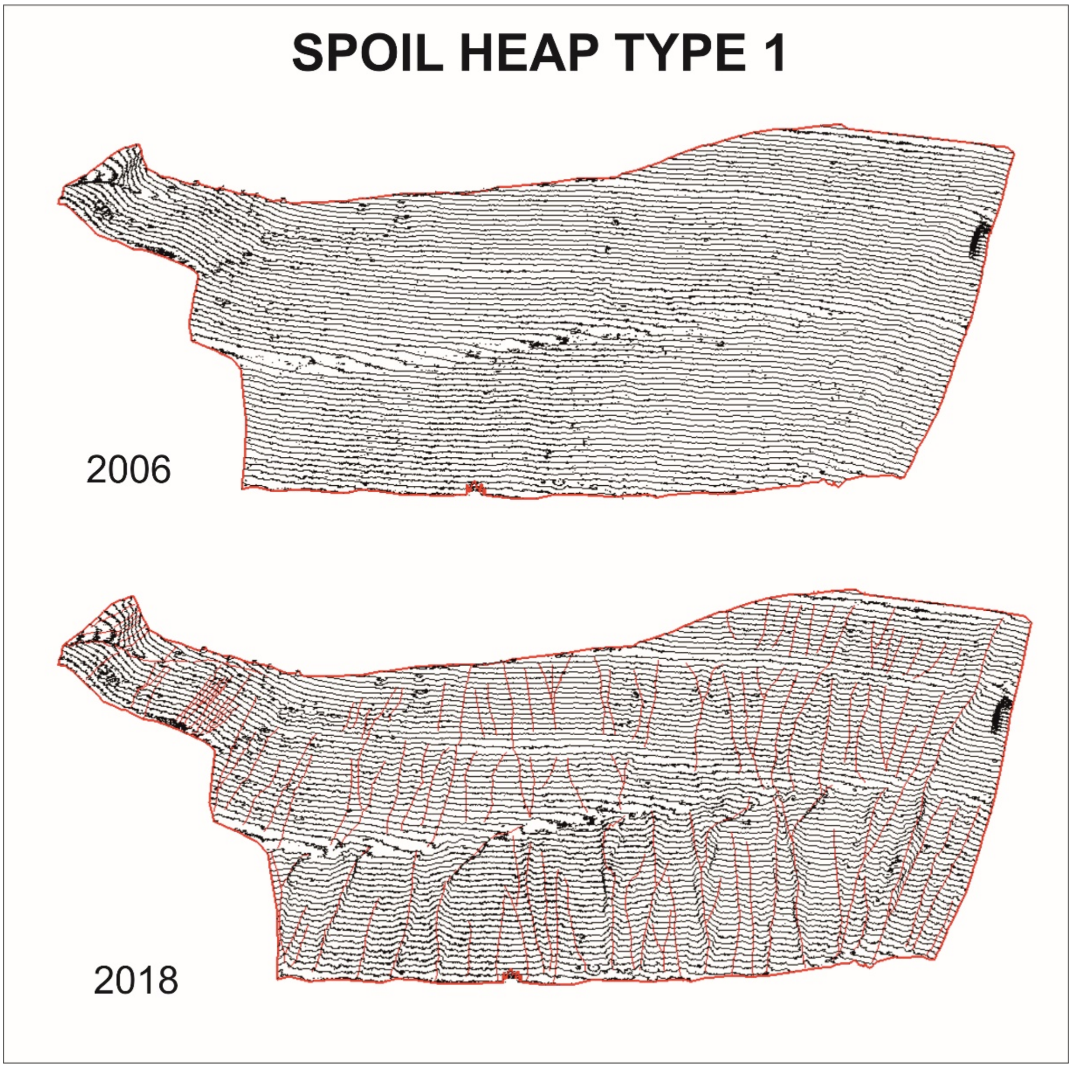

Figure 5. 3D view of spoil heap type 1 in 2006 (reconstructed) and 2018 (current situation)

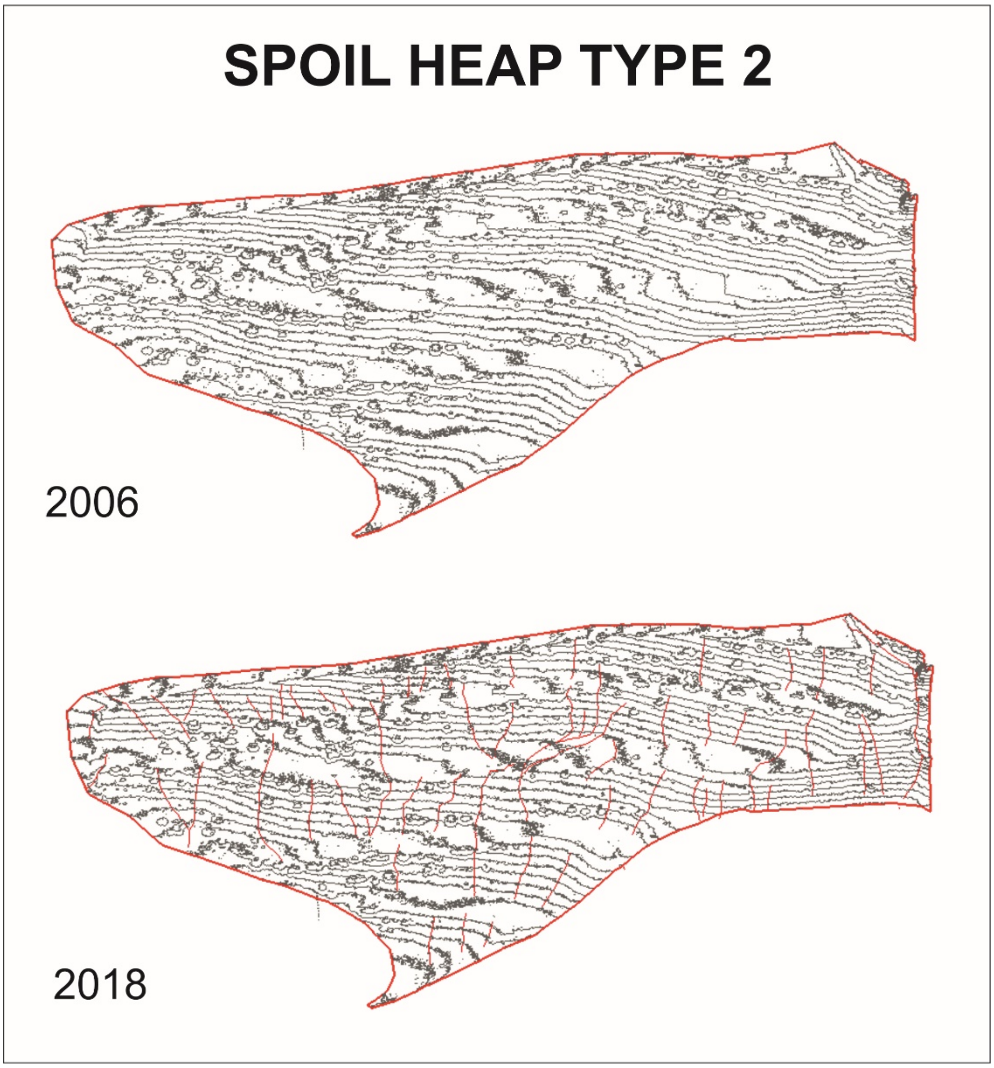

Figure 6. 3D view of spoil heap type 2 in 2006 (reconstructed) and 2018 (current situation)

Results

Table 2 shows the rills and gullies density results. It is possible to observe that the spoil heap type 1 has higher rill and gully density than the spoil heap type 2.

It is important to highlight that these values should be considered as the minimum, because it was not possible to draw the smallest rills, due to the orthophoto resolution. It is to say, rill/gully density is likely to be higher than the obtained values.

Table 2. Rill and gully density results

Spoil heap type	Total rill-gully length (m)	Area (m^2)	Rill/gully density (m/m^2)
Type 1	2609.18	19516.73	0.13
Type 2	1136.78	18217.67	0.06

Table 3 shows the mean annual total erosion (equivalent here to sediment yield). Calculations have been made for both spoil heaps due to, although they could have different erosional behaviour because its own characteristics (narrow or wide berms), in this case, erosion have affected both spoil heaps and they behave as a single system.

As explained in the rill and gully density results, the obtained values should be considered as the minimum, due to the fact that some small rills are not detectable by the method followed, and also that sheet erosion has not been considered in this study. In other words, the mass of sediment eroded in both spoil heaps is likely higher.

Table 4. Volume and mass of sediment eroded at the two spoil heaps studied since its regrading, 2006–2018. The sediment yield (calculated for 12 years) is also included.

Spoil heap	**Area (ha)**	**Volume of eroded waste (m^3)**	**Bulk density (g/cm^3)**	**Mass of eroded waste (Mg)**	**Annual erosion-sediment yield (Mg/ha/yr)**
Type 1 + Type 2	3.77	2968.45	1.54	4571.42	101.05

METHODOLOGY

The geomorphological evolution of the restored area has been measured in terms of the formation and development of rills and gullies and the incision of the streams and channels. **The indicators have been**:

- Density of rills (m/m^2)
- volume of rills (m^3/m^2)
- rills erosion rate (kg/ha)
- channel incision upward (m/m; %)

Surface water erosion – which acts in restored areas – has two forms: concentrated erosion (rills and gullies) and sheet erosion. The first is responsible for most of the erosion and is easily measurable, which is why it is used to assess erosion in restored mining areas (Nicolau & Asensio, 2000). These measurements have been carried out in 3 moments:

- Initial moment, after restoration: 04.11.2019 (Digital Elevation Models, MDE)
- Year 1 after restoration: 23-24.05.2020 (MDE)
- Year 2 after restoration: 17-18.03.2021 (Field measurements)

Two methodological approaches have been used to obtain the data. On the one hand, Digital Elevation Models (DEM) obtained from aerial photographs taken with a drone and, on the other, direct field measurements of rills and gullies. The DEMs were used for the 2019 and 2020 measurements (as well as for the baseline). The applied procedure is explained in the following section. The field measurements were taken in 2021. The reason for the methodological change is due to the fact that the growth of the vegetation from the second year of restoration distorted the DEM, generating significant errors in the measurements. It is a well known technical problem that, currently, can only be solved by incorporating lidar technology into drones, which is done by very few companies and at very high prices. For this reason, it was decided to carry out direct measurements of rills (sampling), as explained in the corresponding section.

The methodology used to monitor the baseline has already been explained in the corresponding section. In the restored area, the same methodology has been applied, as well as others, as explained below.

Topography evolution from MDE/aerial photographs

For the digitalization of the erosive forms, orthophotos and the DEM elaborated using the Structure from Motion photogrammetric technique (Carrivick et al., 2016) were used as sources. This procedure is based on the creation of a dense point cloud from photos and control points processed with photogrammetric software. In this case, the field surveys were carried out on 04.11.2019 (at the end of the restoration work) and on 05.23-24.2020 (one year after completion). The photographs used were aerial and were taken with a DJI drone, a service contracted from the company DGDRONE (www.dgdrone.com). The control points were measured with differential GPS and the subsequent processing was carried out by the team from the Complutense University of Madrid (UCM). To carry out this task, the Agisoft Photoscan software was used. Once the point cloud was obtained, two other topographic products were acquired (those used in this work), which were the Digital Elevation Models (DEM) and the georeferenced orthophotos, all of them in raster format. The management of this methodology is the most used to observe rapid changes in the ground surface (Kou et al., 2020; Hancock et al., 2008). The treatment and analysis of the DEMs and the orthophotos were carried out using the QGIS program, a software specialized in Geographic Information Systems.

Using the 2020 DEM and its associated hillshade file as a base, the main channels and secondary erosional forms deeper than 2 cm have been mapped.

Annual erosion rate estimation

The apparent geomorphological changes in restored area were estimated by directly comparing the two DEMs from 2019 and 2020. This process was carried out using the Digital Elevation of Differences (DoDs) (raster files that represent the difference in elevation between both topographies). These files do not make a mere direct comparison of the relief, but also take into account the degree of accuracy of each topography, that is, how much they resemble reality. This process was carried out using the Geomorphic Change Detection software and methodology (Wheaton et al., 2010). This allows the differences in elevations of the DoDs to be translated into volumes and assigned an uncertainty value based on the errors inherent in any topographic product.

This tool has been chosen for its simplicity, although its application has some problems. On the one hand, there is the difficulty of visualizing the difference between vegetation and bare soil in the DEMs (Wheaton et al., 2010). Although an attempt was made to eliminate the effect of this factor in the data generated, it is very difficult to eliminate it completely, so the volumetric changes, in part, correspond to plant growth and not to a geomorphological change in the area. This is a widely recognized problem when working with topographies derived from photographic products. Also, in newly restored lands, the soil supports different elevation changes not subject to land erosion, but are recorded with the DoDs. These are due to the presence or absence of water and temperature changes (Vericat et al., 2014). To reduce the effect of these problems, the comparisons have focused on areas with large signs of erosion and little vegetation.

Topography evolution from field measurements

<u>Rills measurement procedure</u>

In order to make better measurements of the erosive forms and to be able to calculate the density of the rills and the loss of accumulated sediment until the year 2021, the method developed by Cermeño in 2017 was applied. This procedure is based on the measurement of the rills in situ, differentiating between whether it is a confined or a dendritic network (Figure 9). In addition, this method assumes that the geometry of a rill is similar to a trapezoid, measuring the surface width (a), the bottom width (b) and its depth (c) (Figure 10) to later extract the total volume data of lost soil.

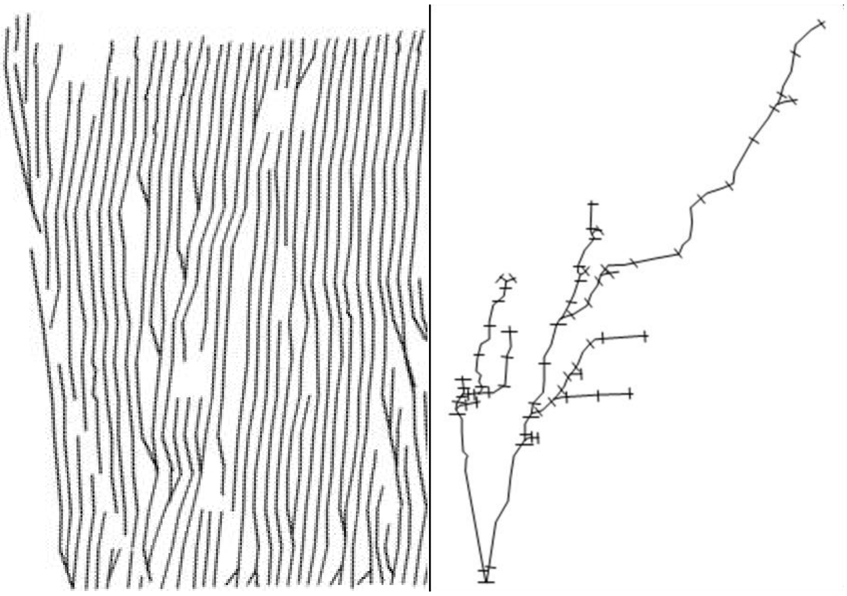

Figure 9. On the left, an example of a confined rill network. On the right, an example of a dendritic rill network. Source: Cermeño, 2017

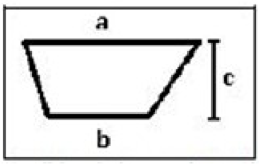

Figure 10. Scheme of the measurement method of a stream according to Cermeño (2017). “a” is the surface width, “b” the bottom width and “c” the depth.

According to this methodology, the way of measuring confined and dendritic networks is different. In the former, a measuring instrument is extended along the entire network and divided widthwise into sections. In this way, the position of the rills that pass between the two instruments is noted on the record and their surface and bottom width and depth are measured. For dendritic networks, one starts from the end of the network to the beginning of the erosive forms. In this network, the surface and bottom width and depth are measured at each of the intersections of two or more streams (Figure 11).

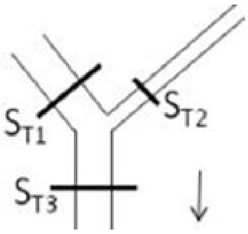

Figure 11. Example of confluence between streams and their measurement. Source: Cermeño, 2017

In the Fortuna quarry, it was assumed that the rill networks are of the confined type, whose measurement is simpler. In addition, this methodology was modified for the calculation of the volumes of sediment dislodged by the rills, since it was not easy to observe and measure the lower width of the erosive forms. In this way, the measurements made in the networks of streams developed in the quarry were limited to measuring the surface width of the stream (a), its depth and its location.

Rills sampling procedure

Field measurement of rills network was not possible to be carried out in the entire restored area because of its large area. So that, a representative rills sample has been studied. Applied sampling method has been double. First, some homogenous units have been identified in the restored area. Then, a systematic sampling has been applied in each homogeneous unit in order to take the measuremnts of each rill. Field work was carried out on March, 17th and 18th.

Homogeneous units were identified taking into account two criteria: a) the quality of the geomorphological restoration in terms of topography (canonical or abrupt) and substratum (colluvium or overburden); b) the main environmental factors wihc control rill formation. These are the type of landform (convex or concave) and the exposure. The following are the homogeneous units that have been considered (Figure 12):

- GeoFluv - overburden substrate - convex (hill) landform (Code 1)

- GeoFluv - overburden substrate - concave (valley) landform (Code 2)

- Canonical GeoFluv - colluvion - convex (hill) (Code 3)

- Abrupt GeoFluv (“Fishbone”) - berm and slope in south exposure (Code 4)

- Abrupt GeoFluv (“Fishbone”) - berm and shady slope (Code 5)

- Abrupt GeoFluv - concave (valley) landform (Code 6)

- Abrupt GeoFluv - convex (hill) landform (Code 7)

- Canonical GeoFluv – concave (valley) – shady (Code 8)

- Canonical GeoFluv - convex (hill) - shady (Code 9)

- Canonical GeoFluv – concave (valley) – south exposure (Code 10)

- Abrupt GeoFluv no revegetated (Code 11)

- Abrupt Geofluv – flat area (Code 12)

Tecmine restoration of Fortuna quarry has two main separated scenarios: the eastern basin (“Small GeoFluv”), where no trees were planted nor holes were open; and the western basin (“Big GeoFluv), where revegetation included trees plantation in holes. As no rill generation was observed in the eastern basin, rills networks were only measured in the western basin.

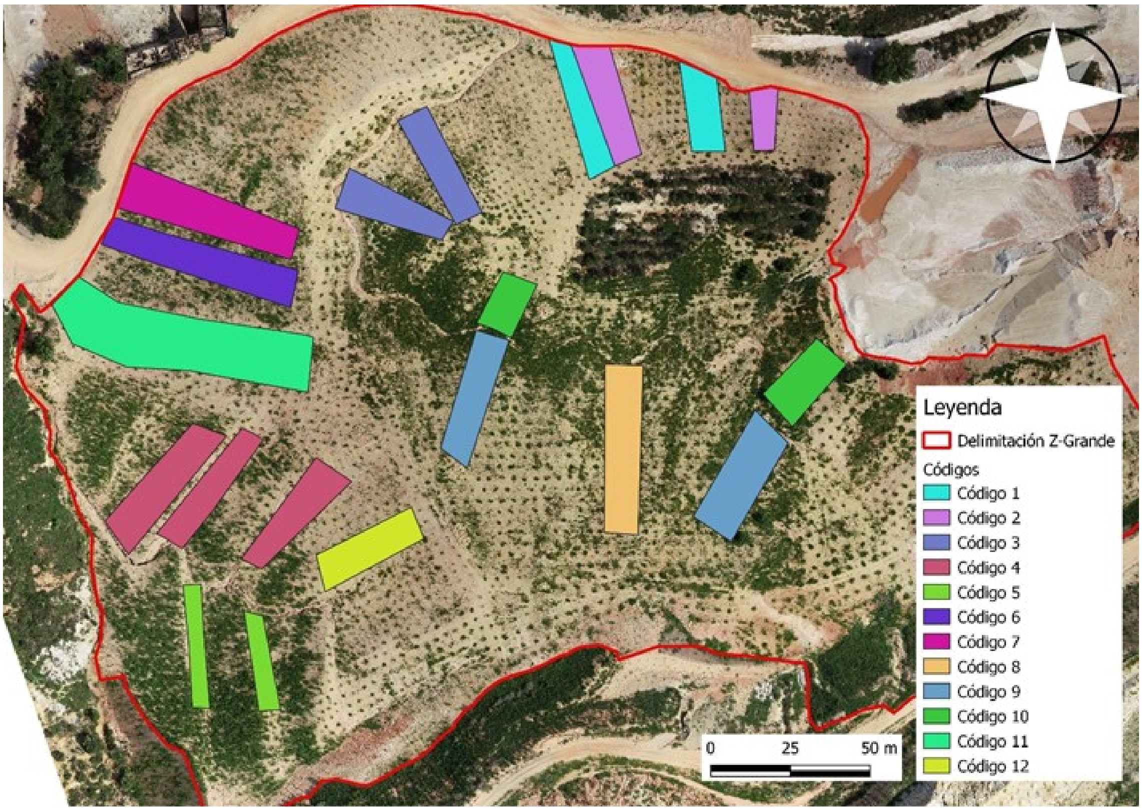

Figure 14: Sampled plots of the different homogeneous units

Systematic sampling in each homogeneous unit was carried out in 5 transcts, where width and height of each rill were measured (Figure 15).

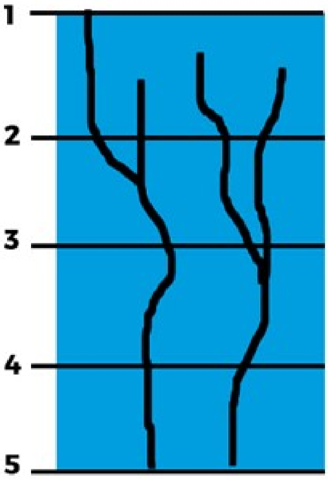

Figure 15. Scheme showing the 5 transcts of the systematic sampling

Transects were set up with a 50 meters long tape. Measurements about rills size (height and width) were taken with a 2 meters long tape.

<u>Density of rills</u>

The methodology used to analyze the density of rills in the 2019-2021 period is based on counting the number and length of the rills located on the sampling plots. Then, the number of rills per square meter and length of the rills per square meter were obtained.

In order to compare rills density in 2020 and 2021, the different homogeneous units were grouped in the thrre categories considered:

- Conventional Geomorphological Restoration: Units 3, 8, 9 and 10.
- Abrupt Geomorphological Restoration: Units 4, 5, 6, 7, 11 and 12.
- Overburden covered areas: 1, 2.

Volume of rills

To measure the volume of soil loss, or dislodged soil, in the gullies, it is only necessary to use the calculation of the area of a rectangle (Equation 1)

$A = a * c$ (eq. 1)

A = section area; a = surface width; c = depth

It is essential to know the distance between the sectional areas (L) in order to calculate the volume of soil dislodged. In this case, the length between the sections (L) was equal to the distance between the five transects represented in the plots. The formula that determines this volume will be the one indicated in Equation 2.

$V_{section} = (A+A1) / 2)*L$ (eq. 2)

Vsection= volume of soil loss between the two sections; A = section area; L= length between sections

The total volume of sediment lost by the network of rills will be the sum of all the Vsections that we obtain.

Once the volume (m^3) of each area was obtained, data were transformed into tons per hectare and year considering that the sediment density is 1.2 g cm-3. In this way, a maximum accumulated soil loss data is obtained in the 2019-2021 period, that is, the maximum rate of erosion for the entire quarry in this period of time. This data can be compared with the total erosion measured in other mining restorations carried out successfully.

Watercourses evolution (upward stream erosion)

Upward erosion in constructed watercourses has been quatified by applying the Cermeño (2007) method. Figures 16 and 17 show the location of the sampled points in the streams of both Western GeoFluv restoration (16) and Eastern GeoFluv restoration (17). Distance among the points is 20 m.

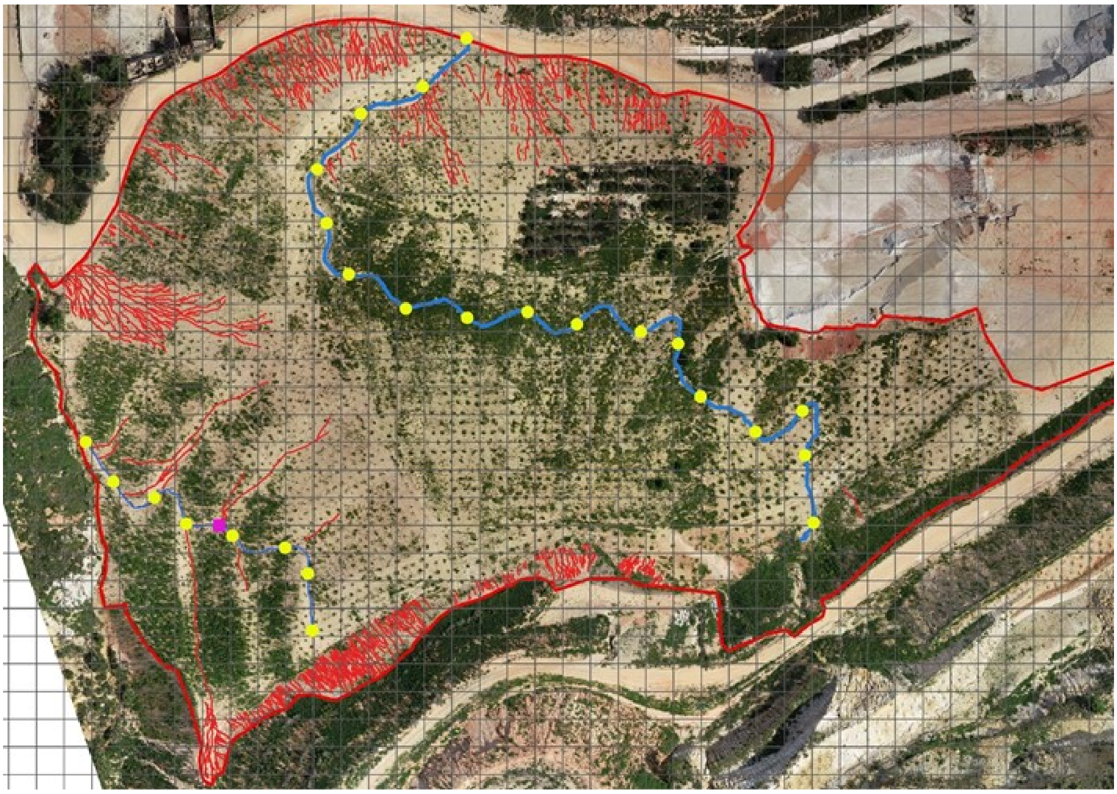

Figure 16. Location of the sampling points (yellow) in the Western GeoFluv restoration. The purple squares represent the start of remounting erosion in the channel in the year 2020.

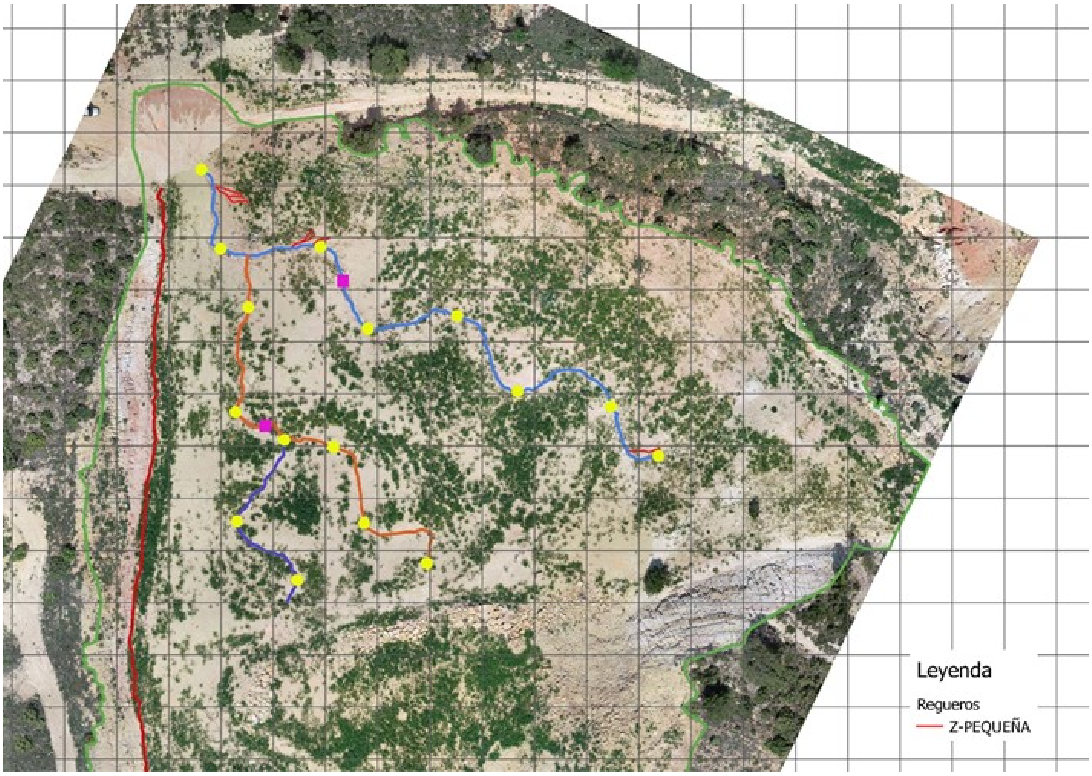

Figure 17. Location of the sampling points (yellow) in the Eastern GeoFluv restoration. The purple squares represent the start of remounting erosion in the channel in the year 2020.

Data collection in the field was carried out with the help of two conventional tape measures (2 meters each). Channel width (top and bottom) and depth were measured.

Data were collected starting at the 0 meter point, which was located downstream of the channel. In this way, it was possible to identify where the exact site where the upward erosion began in March 2021 was located.

Andrea García García has participated in this work with her Master's thesis (García, 2020).

RESULTS

Rills network development

The results obtained are shown in 3 graphs.

Figure 18 shows the rills density evolution between 2019 (still without rills) and 2021 (March). The following observations stand out:

- In Eastern GeoFluv (=Conventional GeoFluv without tree holes) no rill networks have been developed.
- In Western GeoFluv, the zone restored by “Conventional GeoFluv with tree holes” has evolved from 0.03 to 0.16 m/m2 in rill density between 2020 and 2021.
- In Western GeoFluv, the zone restored by “Abrupt GeoFluv” has evolved from 0.01 to 0.62 m/m2 in rill density between 2020 and 2021.
- In Western GeoFluv, the restored zone with overburden substrate has evolved from 0.24 to 0.32 m/m2 in rill density between 2020 and 2021.

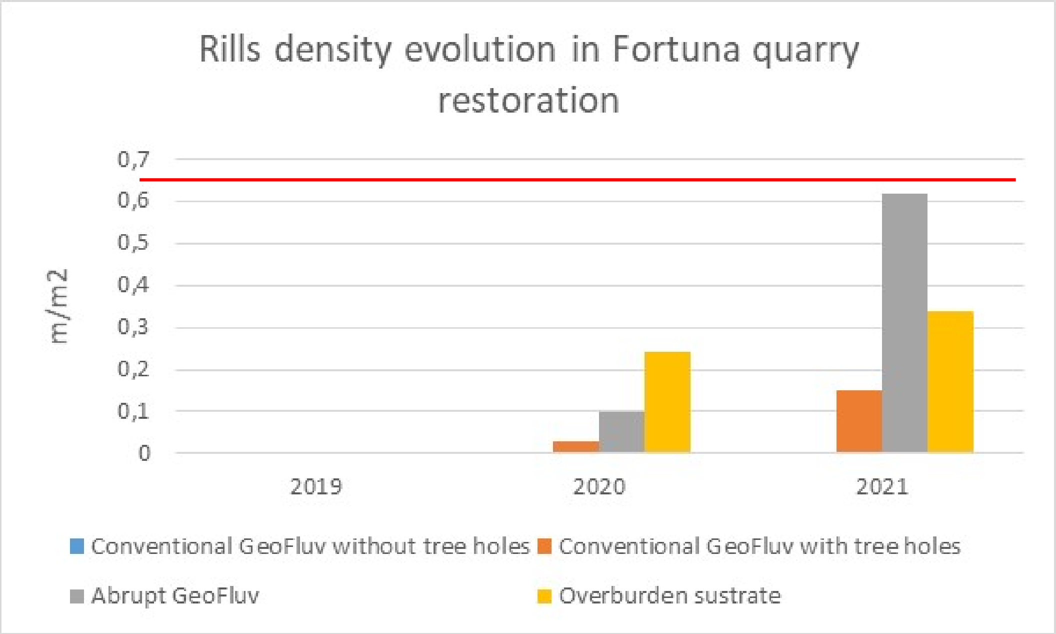

Figure 18. Rills density evolution (m/m^2) in 2 years after Fortuna quarry restoration. Different types of treatments are compared: Conventional GeoFluv restoration without tree holes (eastern Tecmine restoration) has not developed rill networks. Conventional GeoFluv restoration with tree holes (gentle slope angles and colluvium substrate) develop low density rill networks. Abrupt GeoFluv restoration (steep slope angles and low quality colluvium substrate) has reached rill density values, which are closed to the erosion threshold compatible with vegetation growth. Areas no covered by colluvium (overburden substrate) ara also included. Red line in the top

shows the maximum tolerable value of rill density in order vegetation can growth, according to Moreno de las Heras et al. (2009; 2011).

Figures 19 and 20 displays the rill erosion magnitude in the homogeneous units, in terms of rills volume per surface (figure 19) and rills erosion rate (figure 20). The outputs of both grpahics are similar. The Abrupt GeoFluv restoration has the highest rill erosion rates. They are especially high in the experimental zone without revegetation (11) and, in a second level, the concavities (6) and sun exposure (4). The areas with Canonical GeoFluv present the lowest values and the areas with overburden, intermediate values.

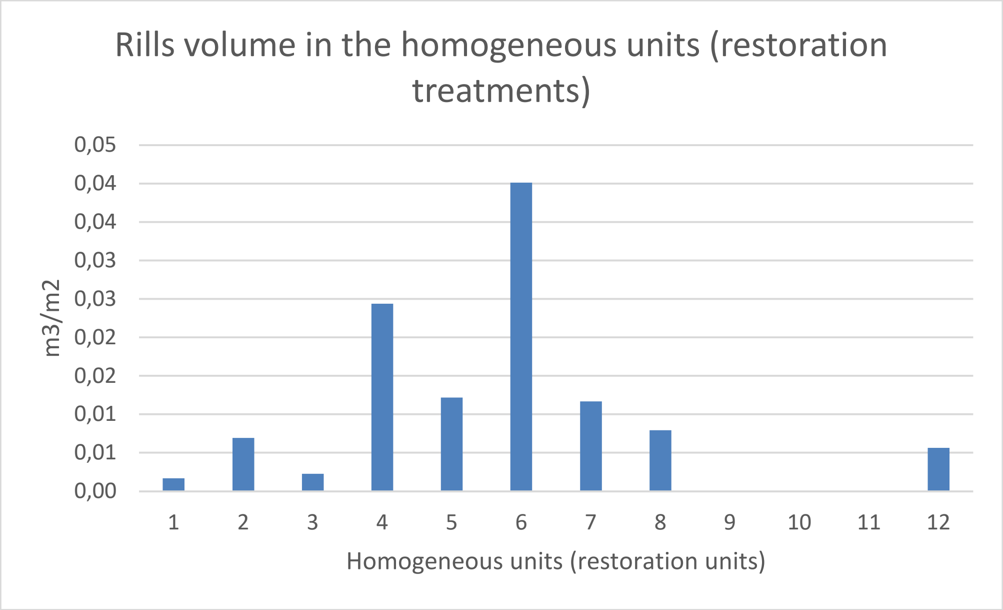

Figure 19. Rills volume per surface (m^3/m^2) in the homogeneous units, 2 years after Fortuna quarry restoration. Homogeneous units are as follows:

- GeoFluv - overburden substrate - convex (hill) landform (Code 1)
- GeoFluv - overburden substrate - concave (valley) landform (Code 2)
- Canonical GeoFluv - colluvion - convex (hill) (Code 3)
- Abrupt GeoFluv (“Fishbone”) - berm and slope in south exposure (Code 4)
- Abrupt GeoFluv (“Fishbone”) - berm and shady slope (Code 5)
- Abrupt GeoFluv - concave (valley) landform (Code 6)
- Abrupt GeoFluv - convex (hill) landform (Code 7)
- Canonical GeoFluv – concave (valley) – shady (Code 8)
- Canonical GeoFluv - convex (hill) - shady (Code 9)
- Canonical GeoFluv – concave (valley) – south exposure (Code 10)
- Abrupt GeoFluv no revegetated (Code 11). Not included in the figure.
- Abrupt Geofluv – flat area (Code 12)

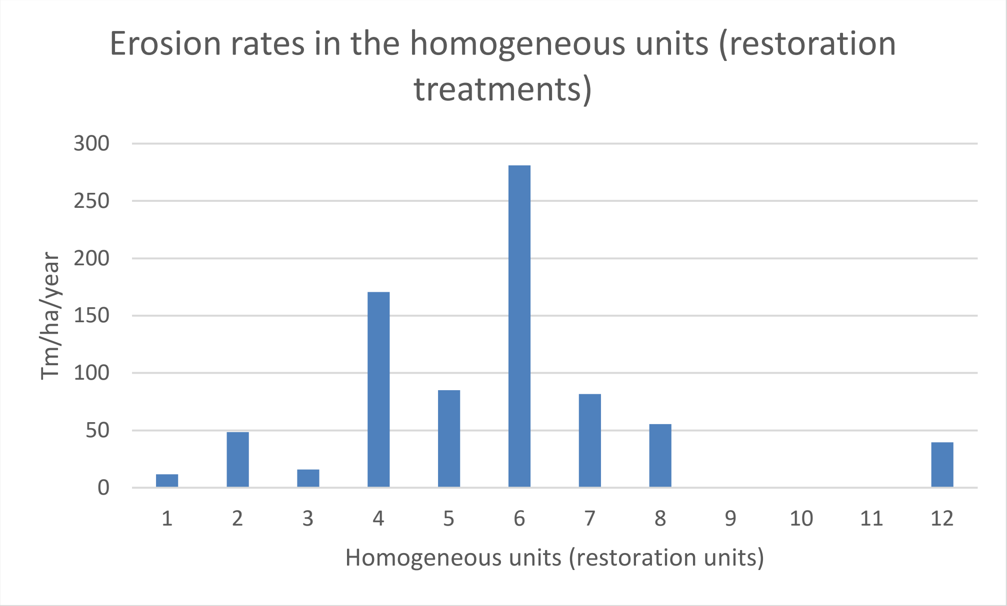

Figure 20. Rills erosion rate in the homogeneous units, 2 years after Fortuna quarry restoration. Homogeneous units are as follows:

- GeoFluv - overburden substrate - convex (hill) landform (Code 1)
- GeoFluv - overburden substrate - concave (valley) landform (Code 2)
- Canonical GeoFluv - colluvion - convex (hill) (Code 3)
- Abrupt GeoFluv (“Fishbone”) - berm and slope in south exposure (Code 4)
- Abrupt GeoFluv (“Fishbone”) - berm and shady slope (Code 5)
- Abrupt GeoFluv - concave (valley) landform (Code 6)
- Abrupt GeoFluv - convex (hill) landform (Code 7)
- Canonical GeoFluv – concave (valley) – shady (Code 8)
- Canonical GeoFluv - convex (hill) - shady (Code 9)
- Canonical GeoFluv – concave (valley) – south exposure (Code 10)
- Abrupt GeoFluv no revegetated (Code 11). Not included in the figure.
- Abrupt Geofluv – flat area (Code 12)

Upward erosion in watercourses

Quantification of upward erosion in the 4 GeoFluv streams is shown in table 5. Channel constructed on Abrupt GeoFluv gives the highest erosion values and those constructed on Conventional GeoFluv give lower records, although channel erosion is higher in Eastern area than in western one.

Table 5. Upward erosion in GF streams

Stream name	Stream length (m)	Stream volume (m^3)	Upward erosion (m) 2020	Upward erosion (m) 2021	Upward erosion (% of stream length) 2021
Western area Conventional GeoFluv	409,33	9682,375	-	125	30,5

Western area Abrupt Geo-Fluv	142,15	41,8285	70	110	77,4
Eastern area Central stream	91,8	17,112	35	45	49,1
Eastern area Eastern stream	138	38,8325	50	80	58,0

DISCUSSION

The evaluation of rill networks is the best indicator of the ecological effects of erosion in restored mining areas. In the Tecmine project, two methodologies have been applied for its quantitative estimation. First, DEMs were used based on photographs taken with drones. However, vegetation growth in the second year produced distortions in the DEMs, making this methodology unfeasible until it is possible to use lidar technology in drones. Therefore, in 2021, rill measurements were taken in the field on a representative sample of the restoration as a whole.

Several indicators of rill erosion have been used from field measurements. The most direct and reliable indicator is the rill density (m/m2). The values obtained indicate that the canonical geomorphological restorations (GeoFluv) are very little erosive. This implies, on the one hand, that they present favorable conditions for the development of plant communities and, on the other hand, that they emit little sediment to the natural drainage network. Indeed, in the eastern restoration zone ("Small GeoFluv") the formation of rills has been practically nil. The western ("Big GeoFluv") canonical GeoFluv restorations - where it has been possible to build a smooth topography and place a colluvium substrate - has developed few rills (0.15 m/m2). In any case, these are densities well below the 0.60-0.70 m/m2 that are considered the threshold above which erosion prevents vegetation development in restored mining areas very similar to Fortuna quarry (Moreno de las Heras et al, 2009; 2011). However, in areas where canonical geomorphological restoration could not be applied -mainly due to lack of space- the density of streams is close to this threshold value and, in some specific areas, exceeds it. Specifically in unit 11, which corresponds to an experimental area that was left without revegetation, so it is not representative of the restoration of the Fortuna quarry. The absence of colluvium type substrate also favors the formation of rilling as others authors have recorded in similar conditions (Martín-Moreno et al., 2016). In Fortuna quarry, rill erosion in overburden covered slopes shows values within the tolerance range.

The estimated rill density in the conventional dump -taken as baseline- varies between 0.06 and 0.12 m/m2, very low values. These values were obtained from the DEM, a method that underestimates the rill density compared to direct field measurements, so we do not consider it as a valid reference.

Hanckok et al. (2016) showed how erosion rates in restored mining areas reach the highest values in the first year after restoration -when rill networks are formed- and decrease exponentially until stabilizing in the fourth year. The rill erosion values recorded in Fortuna quarry correspond to the initial phase of rill formation. Therefore, it is foreseeable that the values recorded will decrease in the coming years until they stabilize. To verify this, field measurements will be carried out in the next two years, as an after Life activity. Erosion rates in abrupt GeoGluv restoration have been very high, so that this zone should be monitored next two years in order to consider if additional treatments msut be applied. One of the consequences is the emission of sediments to the natural drainage network (off site effects) since this abrupt GeoFluv area is closed to a natural creek.

The other erosion process that is characteristic of restored mining ecosystems is the encroachment of constructed streams. Erosion in streams is more related to off-site effects, as the materials removed are more likely to reach the natural drainage network. In theory, GeoFluv channels should not evolve by upward erosion, as long as the channel profile is connected to the natural base level. However, at Tecmine there have been deviations between the design of the channels in plan and their execution, with upward erosion affecting 30.5% of the length of the western restoration channel ("Big GeoFluv"); and between 49 and 58% of the length of the eastern GeoFluv channels ("Small GeoFluv"). This phenomenon has been triggered by high intensity weather events, such as storms Gloria (2020) and Filomena (2021). It is expected that upstream erosion will continue to progress towards the upper reaches of the streams. In any case, the rates of the backward erosion do not compromise the stability of the restored area as a whole. This has been observed in other GeoFluv restored quarries (Martín-Duque et al., 2020; 2021; Zapico et al., 2018).

In the Abrupt Geomorphological Restoration area, the upstream erosion in the main channel of "fishbone" is really important, affecting 77.4% of the length of the channel. The drainage system designed and built was not adequately dimensioned, so that a large gully has formed with the capacity to evacuate runoff from extreme events. It is advisable to carry out a follow-up of this watercourse in the coming years, as an afterlife activity.

CONCLUSIONS AND FURTHER CONSIDERATION

Measuring erosion in restored mining ecosystems is a methodologically complex, time-consuming and resource-intensive task. The assessment of stream networks is a good approximation and the best indicator of the ecological effects of erosion in these areas. The most reliable method at present to quantify rill erosion is direct field measurement by sampling. The methodology based on the Digital Elevation Model (DEM) obtained from photographs taken with drones has shown great limitations due to the distortion of the DEM, caused by the growth of vegetation. This methodology is unfeasible until it is possible to use lidar technology in drones.

Canonical geomorphological restorations (GeoFluv) are very little erosive. Rill density has been almost null in Eastern GeoFluv area and 0.15 m/m^2 as average in Western area. Values estimated for the conventional dump -taken as baseline- range between 0.06 and 0.13 m/m^2. It should be noted that baseline data were obtained from DEM methodology, which underestimate the real data. On the other hand, rill density values are well below of the threshold value that sets the success of the plant community development (0.60-0.70 m/m^2). That means that the canonical GeoFluv restorations present favourable conditions for the development of plant communities and, on the other hand, they emit little sediment to the natural drainage network. This can also be said for the watercourses, with a moderate upwards erosion.

However, abrupt geomorphological restoration has generated rill networks with much higher density than that of the baseline and closed –but below- to the maximum tolerable rates for plant community can develop. In addition, backwards erosion in the main watercourse is also quite active, which favours sediment emissions to the natural drainage network (offsite effects).

Substratum selection is a key issue to reduce water erosion since colluvium materials give much lower erosion rates than overburden.

The rill erosion data obtained from the monitoring corresponds to the first two years after restoration. This is the most erosive period - the formation of rills - as erosion subsequently decreases exponentially until it stabilises in the fourth year.

AfterLife monitoring is recommended with two objectives: a) monitoring rill network evolution two more years in order to find the stable erosion rates; b) surveying the evolution of the abrupt GeoFluv restoration, if necessary to apply some treatment.

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ANNEXES

ANEXED 1. Justification for the change of the methodology in the monitoring of suspended sediments.

UNIVERSITY OF ZARAGOZA REQUEST

Reasons why it is requested not to use the suspended solids indicator to evaluate the reduction of the erosive impact after the restoration.

One of the benefits of the GeoFluv restoration carried out will be the reduction of the emission of sediments into natural channels. Among the indicators that had been proposed to be used for this is the concentration of suspended solids. This measurement is carried out by taking water samples after major rain events in several places: at the exit of the area restored with GeoFluv and in the Riodeva stream upstream and downstream of the farm. The approach is simple: quantify the concentration of sediments that come out of the restored area, as well as those of the natural riverbed of the Riodeva before and after collecting the water from the mine.

However, this approach has several limitations:

1. Sampling after rainfall is difficult, especially in the outlet channel of the GeoFluv restoration, due to short-lived, ephemeral water flow and very limited access to sampling points in the rain.

2. The samples that are taken are not representative of the volume of sediments that come out of the basins, since they represent a negligible volume of the runoff that is generated. In addition, it is known that the concentration of sediment varies over time during a rain and the samples taken only correspond to the final phase of the hydrograph.

These two reasons – insufficient representativeness of the samples and logistical difficulties – lead us to consider this indicator as unfeasible.

However, the project is working with other indicators that, on the one hand, are accurate in estimating erosion in the restored areas, and on the other, are easy to measure. This is the quantification of erosion by streams that is carried out through two approaches: a) analysis of aerial images taken each year in drone flights; b) Field measurement of the rill networks.

For this reason, as we have other indicators that are more precise and easier to measure than suspended solids, we request permission to eliminate them from the protocol.

UE ANSWER

This is a note to meet the next request of the E.U. evaluation team after the visit on December 2019:

"I understand the sheer difficulties encountered for the measurement of the suspended sediment concentration based on water samples and I accept the abandonment of the direct measurement of this indicator via this method. However, as discussed during the visit of the external monitoring team, there are alternative (indirect) methods to estimate it. Please clarify the methodology finally selected for this purpose in the next visit to the project".

Sediment yield from the restored sites is now being recorded by means of Digital Terrain Models (DTM) constructed from aerial photographs taken from drones. First photographs were taken in august 2020 and following measurement will be conducted in june 2021. 2020's photographs have already been processed. DTMs have been analysed and erosive land forms -mainly gullies and rills- have been mapped and measured. So, a sediment yield estimation is available.

In addition, a second approach will be applied. This will based on field work. Rill and gully networks will be directly recorded by means of measuring tapes next novemeber 2020.

After these measurements, we expect to know the sediment yield magnitude as well as to understand the drivers explaining soil erosion in the restored sites.