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Geomorphic landscape design integrated with progressive mine restoration in clay quarries of Catalonia

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ABSTRACT

Geomorphic-based mine restoration of clay quarries in Tortosa (Catalonia) was co-funded by the European Union's LIFE programme. The landform design was made with GeoFluv-Natural Regrade. Their building was performed with existing machinery pool and operators. The main constraint was the impossibility of setback regrading of pre-existing-benched highwalls. Progressive geomorphic mine restoration neither reduced mineral production nor changed the operations. The approach has resulted in higher landscape functionality and integration. Monitoring showed localised erosion due to poorly planned discharge of road runoff and sporadic tunnel erosion. Sediment movement at the designed drainage network is similar to the local fluvial dynamics.

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1. Introduction

Humans have been ceaseless geomorphic agents since the early to middle Palaeolithic [1]. The Neolithic and the Industrial Revolution involved major expansions to the magnitude of earth movement. Post World War II, the increase of human impact on the Earth's land surface has been dramatic [2].

In almost all cases, earth movement by humans during mining results in land degradation. Mining is essential in our lives, but has also detrimental effects, which have been documented elsewhere, see [3–6]. This includes habitat destruction and fragmentation, biodiversity loss, soil erosion and deterioration, surface and groundwater pollution, among others [7].

We humans also repair such disturbances. The conventional approach in mine rehabilitation develops uniform slopes conforming to neat lines and grades and builds rigid, non-erodible drainage structures designed to handle specific extreme events [8]. However, these conventional approaches too often fail and lead to accelerated erosion [9]. Also to channel relocation due to overtopping, washout of erosion protection or channel degradation [10]. Without constant maintenance, which is usually not economically feasible, most mine rehabilitation landforms gradually erode, evolving to resemble natural ones [11]. To avoid such problems, a call has been made for the application of geomorphic principles in the design of mined land rehabilitation [12,13], to integrate mine lands water management into ore extraction operations [14,15].

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In this regard, we have now the knowledge, resources and technical capacity to design and construct landforms and landscapes that replicate the geomorphic, hydrological and visual functionality of their natural counterparts [16,17]. This speciality is called 'geomorphic reclamation' (also rehabilitation or restoration), which has been mostly applied at mining sites [18].

Restoration, reclamation and *rehabilitation* indistinctly relate to the action of a repairing a damaged ecosystem. *Reclamation* is more common in the US and Canada. In Australia, *rehabilitation* is the usual term. In general, reclamation and rehabilitation of severely disturbed terrain imply incomplete activities to heal damaged ecosystems [19]. Due to the high disturbance that mining implies, they are the usual terms for this activity. *Restoration* presents the highest impact correction to ecosystems, in terms of their structure and function [20]. The three terms apply to 'geomorphic'. Here we use *geomorphic restoration*, meaning that a geomorphic approach maximises the recovery of disrupted ecosystem structure and functionality. In terms of geomorphic dynamics, geomorphic restoration creates a steady-state landscape with approximate balances among erosive forces and resistances [13]. Overall, it establishes a basis for a true recovery of functional landforms and landscapes on lands disturbed by mining, and for the replenishment of ecological goods and services [17].

Independent of the essential need for mining, it seems beyond doubt that we need to restore, as best we can, the legacy of our transformations and deformations, recognising also the impossibility of many cases. But perhaps we cannot continue common current practises, which basically implies dumping wastes or building monolithic structures with them at excavated sites. These practices are objectively unsustainable [2].

The human biogeomorphic work of mining is not entirely different from the work of many other organisms that alter Earth's surface to suit their own convenience and comfort. What is now new is the extent of our actions, our extraordinary technological capacity to move earth and the tremendous detrimental effect on our life-support systems [2]. For example, as it is well known, the careless disposal of waste rock or mine tailings in mountainous areas has triggered many catastrophes, see [21].

The need for ecologically restoring lands degraded by human earth movement activities such as mining is clear. There is no stronger evidence than the fact the United Nations declared the period 2021–2030 as the Decade of Ecosystem Restoration, contributing to combat climate change and safeguard biodiversity, food security, and water supply. The role of geomorphic restoration for such an ambitious goal is key [17].

If we want to maintain terrestrial life-support systems, a paradigm shift in current extractive activities is needed, concurrent with abandoned mine restoration. This paradigm shift is urgent; but how do we, and how should we, transform mined lands? The concept of restoring the land in parallel with transformative earth movement is well established in what it is called progressive rehabilitation. It involves the staged restoration of disturbed areas during mineral resource extraction, instead of large-scale post-production works, see [22]. It enables mining and restoration to be a coherent, single process. Incorporating the geomorphic approach into this progressive mine rehabilitation can simultaneously rebuild functional landscapes as mineral production earth movements proceed. Philosophically, the idea is not new. It means revitalising the *Design with Nature* concept, see [23].

Geomorphic restoration of land degraded by mining has been carried out mostly in North America. The United States has done more in this regard, in terms of both examples and literature. Attempts to 'recreate' natural landforms that surround a mine site are based on the pioneering requirements included in the Surface Mining Control and Reclamation Act of 1977, (SMCRA [24]). This US law states that the surface configuration achieved by backfilling and grading of a mined area should closely resemble the general surface configuration of the land prior to mining, and should blend into, and complement, the drainage pattern of the surrounding terrain. We know now that surface configuration replication of a pre-disturbed site is not possible, since physical and chemical properties change with mining. Actually, replication premine topographies developed on consolidated rocks with unconsolidated waste can lead to negative environmental effects [25]. But the goal of 'blending into, and complementing, the drainage pattern of the surrounding terrain' is still unique and avant-garde worldwide. In 1999, people began to apply a geomorphic restoration method called GeoFluv to large coal mines of New Mexico (United States), see [26,27]. GeoFluv is consistent with SMCRA and subsequent principles and techniques [28–31]. La Plata mine provides a successful application of this method [32]. From New Mexico, this technique is now spreading all over the world, as this paper reports. Owing to these experiences, geomorphic restoration (reclamation) is officially recognised within the OSMRE Technology Development and Transfer (TDT) program, see [18]. States such as New Mexico have regulations that stipulate that a geomorphic approach to backfilling and grading is the Best Technology Currently Available (BTCA) for coal mine reclamation, see [33].

In Canada, mine restoration based on a geomorphic approach began in the 1990s [10]. Contributions by Canadian practitioners are outstanding, mostly an outcome of the Oil Sands restoration [34]. In Australia, from pioneering work on geomorphic landform design [35,36], geomorphic restoration in mining rapidly spread over the last decade [37–39]. In Europe, geomorphic restoration is almost limited exclusively to Spain. Research and applications started during the mid and late 1990s [8,40], and have since continued [41–43]. The main applications are on kaolin and silica sand mines. Its success has been acknowledged at the European level by the recognition of geomorphic restoration (reclamation) as one of the best available techniques for the management of waste from the extractive industries [44].

At smaller scales are examples of replication of natural landforms at: (i) hard rock quarry faces in the UK since the 1970s [45–48]; and (ii) rock roadcuts in France [49]. These methods simulate time compression by designing and building the 'natural' rock cliffs or scree (talus) slopes that would tend to form and evolve with time through rock falls and slides that occur preferentially on weathered or fractured rocks, with the more resistant rocks outcropping as main rock protuberances. Equivalent natural cliffs or rock slopes are used as analogues. For a synthesis of the use of geomorphic landform design methods, soil erosion modelling, and landscape evolution modelling, in mine rehabilitation, see [16].

This paper describes another example of geomorphic mine restoration, focusing on geomorphic-based progressive exploitation and restoration, within the framework of a LIFE *(L'Instrument Financier pour l'Environnement)* project funded by the European Union (EU).

Progressive rehabilitation has been recognised by the mining industry as a key strategy for minimising mine closure costs and environmental risk [22]. Progressive mine rehabilitation is becoming relatively common worldwide. However, geomorphic progressive mine rehabilitation (restoration), or progressive rebuilding of structured and functional landscapes as the earth movement works advance, is still very scarce. Some exceptional examples in the US [32] and Australia [38] demonstrate its feasibility. To the best of our knowledge, this paper describes the first example (Pastor II) of geomorphic progressive mine restoration in Europe.

2. Material and methods

2.1. Study area

The Aurora, Pastor I and Pastor II clay quarries are on company property of CEMEX, Catalonia, Northeast Spain (296593; 4516984, coordinate system UTM-31 N, datum ETRS 1989). Placed within the Campredó local entity, Tortosa municipality (Tarragona province), they are very near to the Ebro Delta (Figure 1). Within this area, several clay quarries have been exploited since the 1960s. The clays extracted to manufacture cement correspond to blue marls and siltstone of Pliocene age, see [50]. Entisols, Inceptisols and Alfisols, according to the USDA soil taxonomy, are the predominant type of soils.

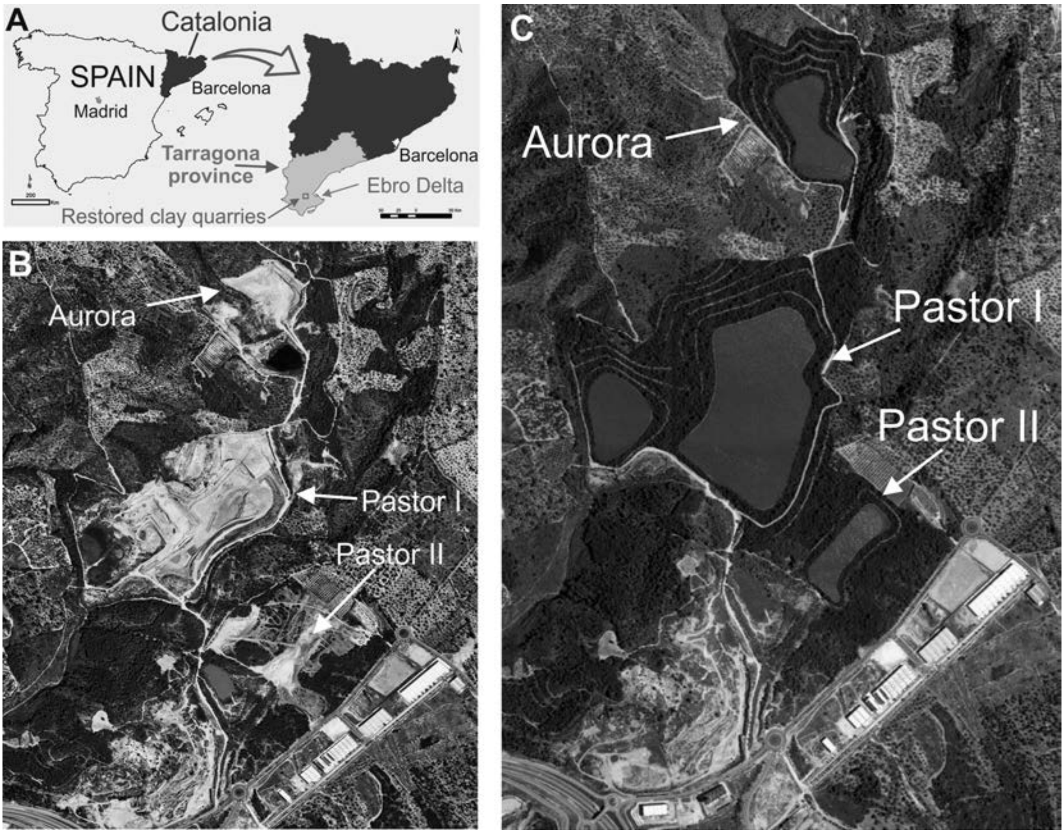

Figure 1. Location of the Aurora, Pastor I and Pastor II clay quarries (a,b). An initial, discarded, traditional restoration solution is shown (c), with terraces for highwalls and ponds for the platforms (source OFTECO).

The climate is maritime Mediterranean, with mild temperatures (14°C mean annual temperature) and 9 months without frost. Mean annual precipitation is 521 mm. Autumn is the rainiest season. The water deficit is between 300 and 400 mm annual mean. The dry period spans the summer months. The rainfall erosive factor, R, is high, characteristic of Mediterranean environments: 185 J m^{-2} cm h^{-1}, see [51].

This mining area is near two protected areas: the *Serres del Cardó-El Boix*, and the *Ebro Delta Natural Park*. The *Serres del Cardó-El Boix* contain holm oaks and Mediterranean mixed woods of a good conservation status. The Ebro Delta hosts the largest wetlands in Catalonia, as well as a rich variety of habitats due to the convergence of marine and mainland environments sustaining great biodiversity. The importance of this Natural Park is recognised worldwide: Natura 2000 and Ramsar site (Convention on Wetlands of International Importance), among others.

The vegetation near the clay quarries is composed of an agroforestry mosaic dominated by maquis and garrigue with palmetto *(Chamaerops sp.)* and forests of Aleppo pine *(Pinus halepensis)*. There are also fields of fruit trees and non-irrigated crops in smaller proportion, most of them abandoned and in process of naturalisation. Before mining operations, crops dominated the landscape in this area. Olive and fruit trees, legumes and cereals were also cultivated on terraces. Due to ceased cultivation, the terraces are becoming deteriorated and the native vegetation is progressively colonising these fields.

Ephemeral watercourses (regionally named *ramblas*) constitute the drainage network. The main watercourses are the Rocacorba and the L'Espluga ephemeral streams. Historic mining operations in this area altered the natural drainage system and continued below the water table resulting in pits becoming ponds after mining ended.

Figure 1 shows the initial landform restoration solution for these clay quarries, with vegetated terraces for highwalls and ponds covering the entire pit floors. This is a non-realistic solution, given the high instability of terraced landforms in this area and the high evapotranspiration, which only allows small permanent ponds.

2.2. Materials characterisation

Landforms denoting active tunnel erosion processes were identified in the existing highwalls of these clay quarries (Figure 2). Tunnel erosion, or piping, refer to the formation of linear voids, or pipes, by the preferential flow of subsurface water in soils and unconsolidated or poorly consolidated materials [52]. Tunnel erosion processes are complex to understand and their occurrence is strongly related to a number of different soil properties [52,53]. Sodic soils with a certain content of exchangeable sodium behave as dispersive soils and potentially develop tunnel erosion, while other soils with exactly the same exchangeable sodium content will not, due to the interaction between many other soil factors [54]. Analysis of EC (Electro Conductivity) and Exchangeable cation content, with emphasis on the exchangeable sodium percentage (ESP), were performed for the clay substrata and wastes, to assess dispersion potential.

2.3. GeoFluv and Natural Regrade

The GeoFluv-Natural Regrade method was used to geomorphically design the new landscapes. It was used after quarrying had finished at Pastor I. A progressive geomorphic mine restoration approach was applied in Aurora, at the end of its Life-Of-Mine (LOM), and in Pastor II from the beginning of its LOM.

The GeoFluv method has been described in both industry [26,27,55] and scientific journals [32,42]. GeoFluv is a fluvial geomorphic method for land restoration, which helps the user to design landforms similar to those that naturally would form by fluvial and hillslope geomorphic processes under the climatic and physiographic conditions at the site. Suitable and stable reference areas need to be identified to provide key input values for the restoration design. Natural Regrade is the software that aids users to make and evaluate GeoFluv designs in a CAD format from the input values [26,55]. GeoFluv first gained recognition after its successful use in coal mines of New Mexico starting in 1999, see [26]. The GeoFluv method designs mature ‘natural’ landforms from the beginning; the method essentially compresses time, creating steady-state landscapes with approximate balances among erosive forces and resistances.

Measurements from specific landscape analogues are needed as model inputs. These reference areas are landforms with earth materials similar to the restoration site. Since mine and quarry wastes are usually unconsolidated materials, alluvial or colluvial analogues are often used. They should be located under similar climatic conditions, where they have adjusted over time to convey water runoff over land without high erosion rates. It is important to note that this goal of ‘stability’ is not zero erosion, but the minimal erosion rates present on local natural land that is not considered to have problematic erosion. Using such inputs to design restoration landforms approaches stability performance comparable to the ‘stable’ reference area landforms. Examples of such measurements are: ridge-to-head of channel distance, drainage density, sinuosity indexes, bankfull and flood-prone channel width and depth, or sub-watershed ridge and swale convex and concave lengths. Precipitation values of Average Recurrence Intervals (ARI) that will relate to the bankfull and flood-prone discharges are also used, as are hydrologic values such as the maximum stream velocity associated with bankfull discharges in the local reference areas [30,31]. In addition to these field inputs and ARI events, a CAD model of the site with its topographic information is needed. Finally, the design area is set, as well as a local base level – point where all runoff will leave the reclamation

Figure 2. Tunnel erosion, piping, at benches of highwall terraces, at the Pastor I quarry.

project area, connecting to a similar level and slope angle, therefore limiting the erosion potential. With all this information, the GeoFluv-Natural Regrade designs are made. The number of potential designs is infinite. The suitable ones are those that meet the earth material volume and operation conditions while fulfiling the condition to stabilise erosion. Besides empirical observations at reference areas, such stability can be predicted by various theoretical methods, including soil erosion models [56], and landscape evolution modelling [57]. Once an optimum alternative is set, either a restoration plan (for an abandoned or end-of-mine site, as in Pastor I), or a progressive mine exploitation and restoration plan (as in Aurora or Pastor II), is drawn. Building the designed landforms directed by staking out or machine control guidance, and monitoring it to verify that the performance is consistent with the design, complete the process. Since the focus here is progressive mine restoration, geomorphic-based, we focus on the Aurora and Pastor II examples.

2.4. The Aurora quarry: design and monitoring

The GeoFluv-Natural Regrade method was applied in Aurora according to site-specific conditions. The quarry interrupted a natural stream course. A nearby groundwater-fed pond existed because former quarrying activities cut into the water table. This pond constituted the local base level for the design of endorheic character. Therefore, a main stem of the drainage network was needed to connect the obliterated stream to the pond. At the time of the design, Aurora was in the latter phase of its Life-Of-Mine, with an existing highwall that would benefit if being regraded, for hydrological functionality and visual integration.

Although the performed analysis on sodium content do not predict high dispersive potential, the occurrence of tunnel erosion is a fact in the area. Therefore, to minimise the likelihood of tunnel erosion, care was taken in landform design and construction to avoid flat areas and remove existing berms to minimise any concentration and prolonged ponding of overland flows [58,59]. Additionally, the whole surface was topsoiled with a stored supply of existing former soils and surficial deposits that draped the exploited clays in the pre-mine scenario.

The re-vegetation plan sought fostering a shrub composition and structure mosaic to nurture various bird habitats, such as for different warbler species. Hydrogels and watering pits were used, in order to favour the harvesting of water and plant survival. Some of the grass and sub shrub seeded species were: *Helichrysum stoechas, Santolina chamaecyparissus, Sanguisorba minor, Medicago minima* or *Cynodon dactylon*. Some of the shrub and tree planted species on ridges and hillslopes were: *Pinus halepensis, Olea europaea v. sylv., Pistacia lentiscus, Jupinerus oxycedrus, Juniperus phoenicea, Rhamnus alaternus, Rosmarinus officinalis* or *Cistus albidus*. And at the drainage network, *Crataegus monogyna, Prunus spinosa, Populus nigra, Sorbus domestica* or *Tamarix africana* among others, were planted.

Landscape evolution of the geomorphic-based restoration of Aurora has been monitored for 6 years from June 2014 to May 2020, through repeated oblique aerial photos, topographical surveys and field work inspections (Table 1).

2.5. The Pastor II quarry: restoration design and staged mine plan

The GeoFluv-Natural Regrade design phase in Pastor II was completed in May 2019. This quarry was in an early phase of exploitation then and amenable to incorporating a truly staged progressive,

Table 1. Monitoring of the Aurora clay quarry.

DATE	TOPOGRAPHICAL SURVEY	OBLIQUE AERIAL PHOTOS	SCENARIO
2014 January	X		Pre-restoration
2014 June		X	
2015 May		X	Restoration
2015 October		X	End of restoration
2016 June	X	X	Post-restoration
2017 June	X	X	
2018 April		X	
2019 December/2020 January	X	X	
2020 May		X	

geomorphic-based exploitation-restoration plan. Two groundwater-fed ponds existed here, as at the Aurora site, similarly moulded by former quarrying activities. Such ponds constituted the local base levels, of endorheic character. Different from Aurora, no interrupted fluvial network or highwalls existed here. An improvement of the geomorphic design for Pastor II, with respect to Aurora, was the armouring of the main channel, replicating the gravel, cobble and pebble sizing and distribution of nearby creeks. The grey clay materials with potential dispersive characteristics found at Aurora did not exist at Pastor II. However, the topsoiling and the revegetation were similar to those at Aurora, with the exception of a focus in creating a forest mosaic with *Pinus halepensis*, blended with areas of open shrub. The aim is to favour feeding areas for the birds of prey of the local ecosystems.

The building process of Pastor II started in June 2019. In January 2020, a small catchment had been restored. The whole course remains in early process phases. Therefore, the erosive and landscape evolution of the Pastor II quarry is much shorter than for the Aurora case, and cannot be reported here.

3. Results

3.1. Materials characterisation

Table 2 gathers the results of selected chemical properties of clay substrata and wastes around the clay quarries under study. Surprisingly, the clay materials in the area can be classified as non-sodic, with low values of exchangeable sodium (on seven of the eight samples).

3.2. Geomorphic analogues

We did not find suitable natural alluvial or colluvial analogues near the quarries. Therefore, we used design inputs obtained from the near Iberian Range of East Central Iberian Peninsula. Three key specific design inputs were [42]: (i) Drainage density of 110 m ha^{-1}; (ii) ‘A’ channel reach of 16.6 m; (iii) Maximum distance from ridgeline to channel’s head of 37 m; (iv) Sinuosity of meandering channels of 1.2. Precipitation values of Average Recurrence Intervals (ARI) that relate to the bankfull (2-year return period, 1-h duration) and flood-prone discharges (50-year return period, 6-h duration) were obtained from the nearest weather station (Tortosa), and yielded 2.98 and 15.06 cm, respectively.

From those inputs, we replicated the ‘A’ to ‘Aa+’ and ‘Cb’ fluvial channels type of the Rosgen morphological classification of rivers [30,31]. ‘A’ to ‘Aa+’ channels have a zig-zag pattern resulting

Table 2. Selected chemical properties of clay substrata and wastes. Mean ± standard deviation values are shown. Number of samples = 3.

		Samples			
Soil Properties	Units	Z1	Z2	Z3	Z4
pH		8.41	8.67	7.91	7.96
Exchangeable K content	µg g^{-1}	83.0 ± 2.0	87.3 ± 10.0	102.3 ± 11.1	94.0 ± 7.0
Exchangeable Mg content	µg g^{-1}	348.7 ± 65.2	213.7 ± 38.8	251.0 ± 12.8	318.3 ± 29.4
Exchangeable Na content	µg g^{-1}	52.4 ± 21.4	93.8 ± 34.7	40.0 ± 5.8	132.9 ± 83.6
Exchangeable Ca content	µg g^{-1}	6703.7 ± 22.2	7460.7 ± 193.3	7460.3 ± 266.2	7583.3 ± 132.1
ESP	cmol kg-1	1.24	2.07	0.87	2.82
Electrical Conductivity (EC)	dS m^{-1}	472	452	374	1171
		Z5	***Z6***	***Z7***	***Z8***
pH		7.93	8.11	7.42	7.96
Exchangeable K content	µg g^{-1}	89.7 ± 2.5	86.0 ± 9.5	136.0 ± 15.7	96.7 ± 6.4
Exchangeable Mg content	µg g^{-1}	314.7 ± 17.6	327.0 ± 74.5	1049.0 ± 106.4	434.7 ± 124.1
Exchangeable Na content	µg g^{-1}	64.5 ± 18.1	55.3 ± 12.4	998.3 ± 329.2	117.3 ± 88.7
Exchangeable Ca content	µg g^{-1}	7459.3 ± 176.4	7883.3 ± 235.5	7222.0 ± 524.1	7177.0 ± 891.2
ESP	cmol kg^{-1}	1.32	1.19	19.14	2.56
Electrical Conductivity (EC)	dS m^{-1}	776	661	4.5	1171

from them flowing around ridges eroded into their valleys walls and they develop on gradients greater than 4%. The GeoFluv method associates these greater than 4% channels with this characteristic zig-zag pattern rather than the sinuous meander bends present in the lower gradient 'Cb' channel type. We fitted such fluvial channels and related hillslopes to the local hydrological, topographic and volumetric conditions of the clay quarries.

3.3. The Aurora quarry: design, building and monitoring

The geomorphic restoration of Aurora covered four hectares. It consisted of planning the recovery of the hydrological connectivity between the ephemeral stream that was interrupted by the quarry and the nearby pond. For that, the main stem of a new drainage network was designed, consisting of a meandering channel, connected upstream and downstream with the natural network (stream and pond, respectively). Three tributaries and associated sub-watersheds were also planned to drain the rest of the restored quarry, opening small valleys in the former highwall and connecting the natural surroundings, upslope of the highwall, with the main channel. However, this connection between the highwalls, the geomorphically restored pit floor, and the topographically undisturbed surroundings was only partial, since an appropriate setback regrading was not possible, due to its proximity to the property boundary. Their backfilling was not an option, due to a lack of waste volume. The highwalls were therefore sub-angularly regraded, replicating mountainous scree or debris slopes, but only with partial geomorphic restoration and integration. The interfluve areas between channels were set on main ridges (divides) with scalloped hillslopes at both sides, with alternating swales and subridges in each slope. Figure 3 shows a layout of the planned drainage network and a 3D perspective view of the final geomorphic design.

The Aurora geomorphic landforms were constructed between November 2014 and September 2015. The machinery pool used for building the complex designed as 'natural-like' landforms was the conventional one used in earth moving and quarrying in the region: excavators, front loaders, bulldozers, and tipper and box trucks. One-week specialised training of the operators was initially needed. The designed topography was staked out at the terrain by using a Leica's differential GPS 1200. The Aurora geomorphic design was planned at the end of its Life-Of-Mine.

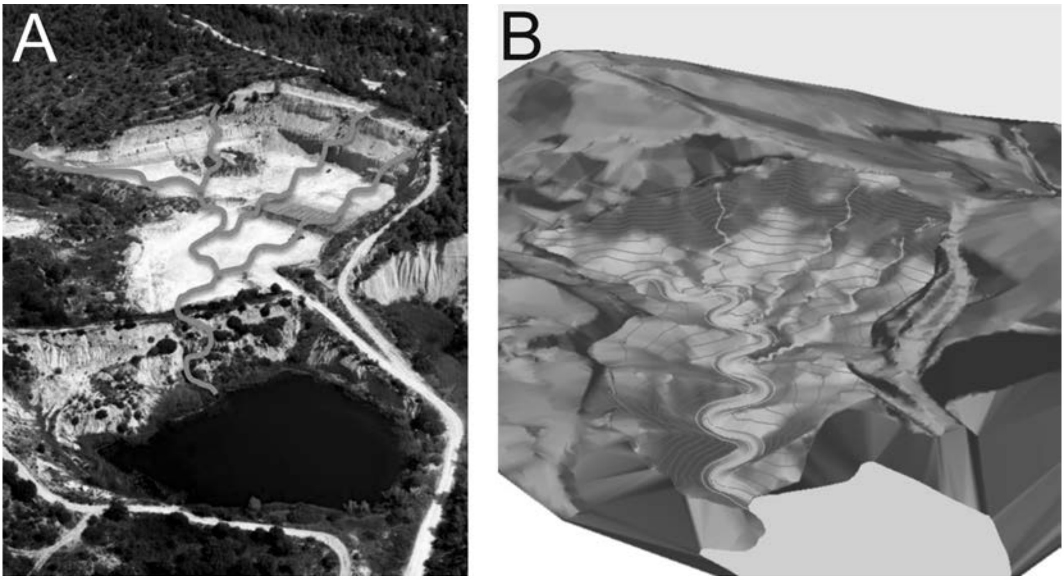

Figure 3. Aurora quarry. (a) Layout of the planned drainage network, depicted on aerial oblique photo of June 2014 (by Paisajes Españoles). (b) 3D view of the GeoFluv – Natural Regrade geomorphic design.

At this final stage, exploitation and restoration were simultaneous (Figure 4). The main channel and the lower part of the three tributaries were excavated on the existing platform, so the final exploitation topography in these areas were final restoration landforms. Figure 5 is a time-lapse sequence of several oblique aerial photos of Aurora.

An analysis of the oblique aerial photos, topographical surveys and field inspections of Aurora showed an adequate landscape recovery. However, minor deviations from the expected results occurred. They were (Figure 6): (a) runoff from vegetation maintenance and watering access roads entered reclamation not designed to accept this runoff, leading to rilling and gullying; and, (b) local piping (tunnel erosion) occurred in specific areas, where the clay waste was not properly covered.

3.4. The Pastor II quarry: design, staged mine plan and phase 1 building

The geomorphological restoration design of Pastor II covers 14.9 hectares. It consists of two main watersheds, each one connected to existing nearby ponds. The hillslope characteristics had the same patterns as for Aurora. Figure 7 shows the final geomorphic design and a 3D perspective view of it.

The main contribution of the geomorphic design of Pastor II is that the design was implemented at the beginning of its Life-Of-Mine, which made possible a staged planning of exploitation and restoration, a truly progressive geomorphic mine restoration. Figure 8 shows the staged exploitation restoration plan (see figure caption for a detailed explanation) and Table 3 the earth movement involved for the main watershed of the design.

The building process of the geomorphic design for Pastor II, according to the new geomorphic approach, started in June 2019. By the end of January 2020, Phase 1, one sub-watershed, had been completed (Figure 9). The machinery pool and topographical survey devices used in Pastor II were the same as used at Aurora. Given the recent completion, no monitoring has yet been conducted.

The paper focuses on the Aurora and Pastor II cases, since progressive (geomorphic) mine restoration is a main topic here, but a sector of the Pastor I quarry has been also subject to geomorphic-based restoration, in this case at an end-of-mine phase (Figure 10).

4. Discussion

4.1. Materials characterisation

Tunnel erosion (piping) occurred in some areas of Aurora where the topsoil was not evenly and carefully spread over some clay wastes. Therefore, despite the results at Table 2 suggest that clay substrata and wastes in the area are not susceptible to present dispersive behaviour regarding sodium content, tunnel erosion is a fact, both at Aurora and near Pastor I (Figure 2). We therefore hypothesise that: (i) there must be other as yet unknown reasons for tunnel erosion, such as the movement of non-cohesive fine particles, but we have no evidences of it; (ii) since ESP test is only one method to assess dispersivity, others (crumb test or double hydrometer) methods may probe the contrary.

Although this is not the main topic of our contribution, the reader should understand that the physical and chemical characteristics of the topdressing material used to establish vegetation on the geomorphic surface can vary from site to site. This project site had clay materials that can have dispersive characteristics that can affect restoration success. For this reason, we recommend that the proper characterisation and expert handling of mine wastes, soils and vegetation be conducted at each site to augment the geomorphic landform restoration. Thus, although the fluvial geomorphic restoration approach promotes steady-state landscape conditions, its use does not exclude the importance of detailed materials characterisation and proper and expert handling of wastes and soils [60].

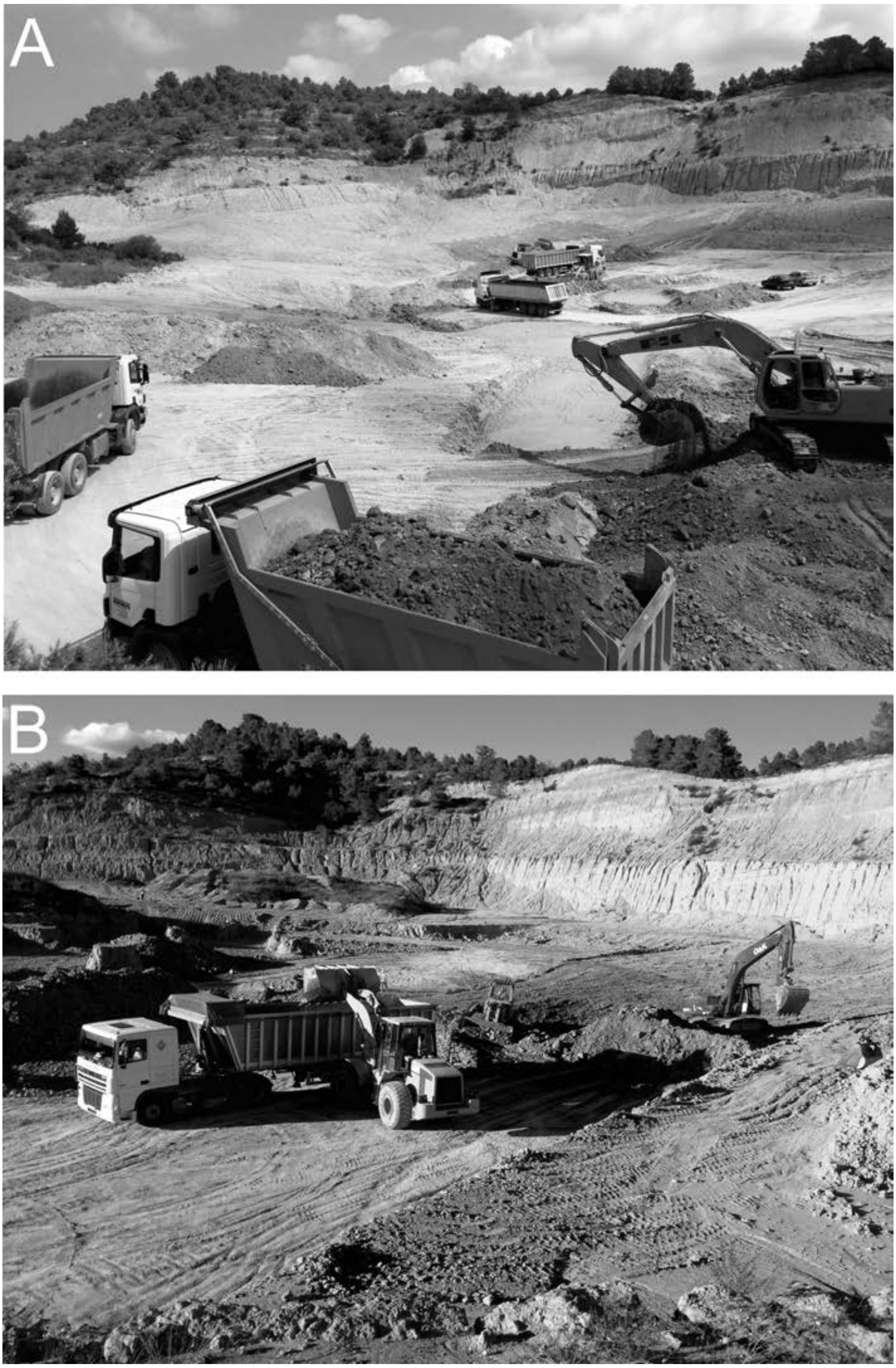

Figure 4. Photos of June 2015 showing the simultaneous process of exploitation and restoration at the Aurora quarry. (a) The two tipper trucks and the excavators, in foreground, are handling topsoil for restoration; the two box trucks and the loader the centre of the image are loading and transporting clay for the cement plant. (b) The loader is loading clay at a box truck (exploitation) whereas the excavator and a bulldozer, to their right, are regrading the final surface according to the geomorphic restoration plan.

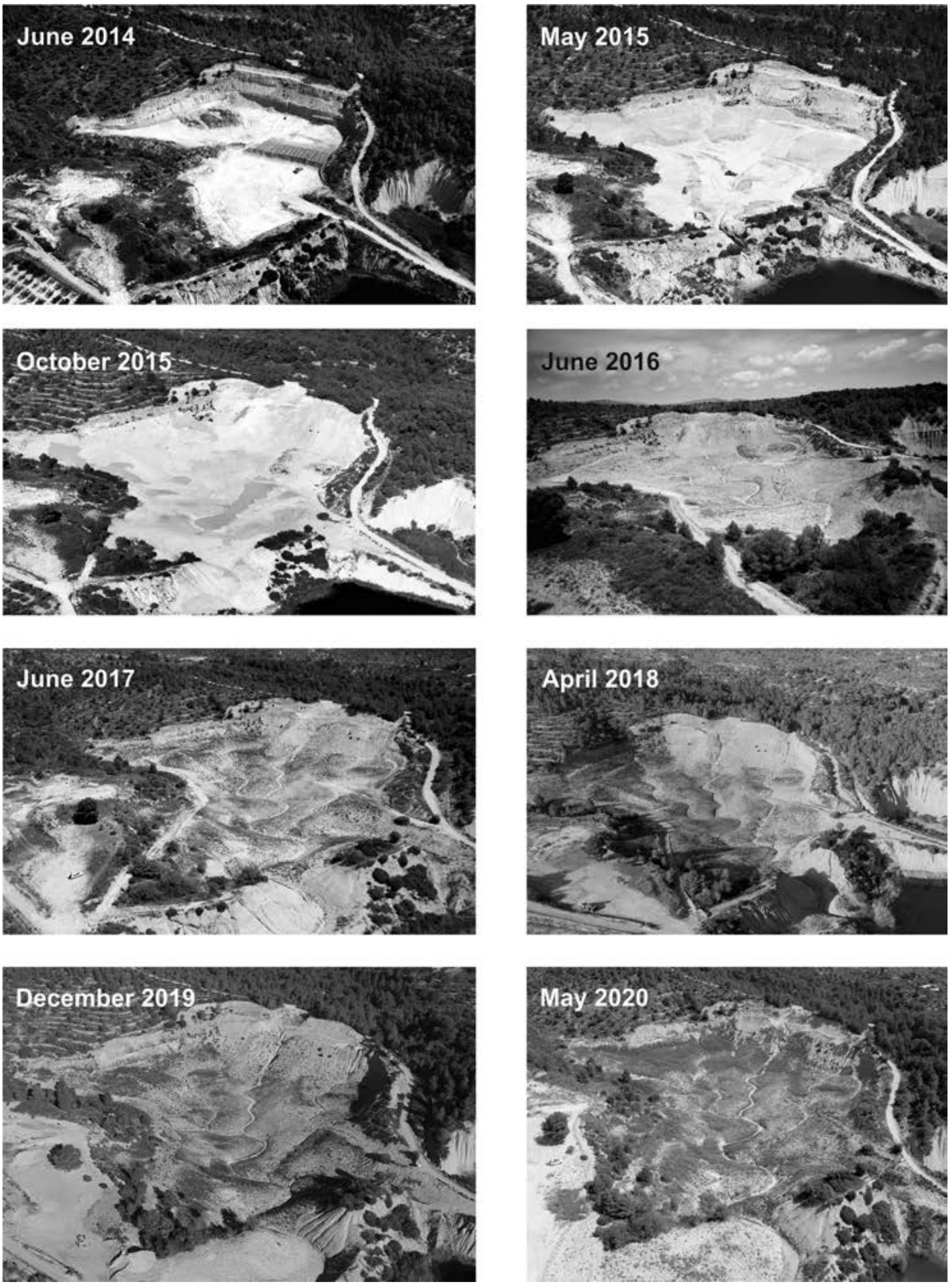

Figure 5. Comparison of oblique aerial photos of the Aurora quarry from June 2014 to May 2020 (photos by Paisajes Españoles and OFTECO).

4.2. On the implementation of the GeoFluv-Natural Regrade method

The application and implementation of GeoFluv – Natural Regrade, for the geomorphic design of the Aurora, Pastor I and Pastor II quarries, has been viable. However, we did not fully mimick the geomorphic natural systems of the environments surrounding the quarries. First, was a lack of site-specific alluvial or colluvial analogues. Second, the most characteristic fluvial systems of the area dry (ephemeral) arroyos *(ramblas)* were not replicated, given the complexity of their design with

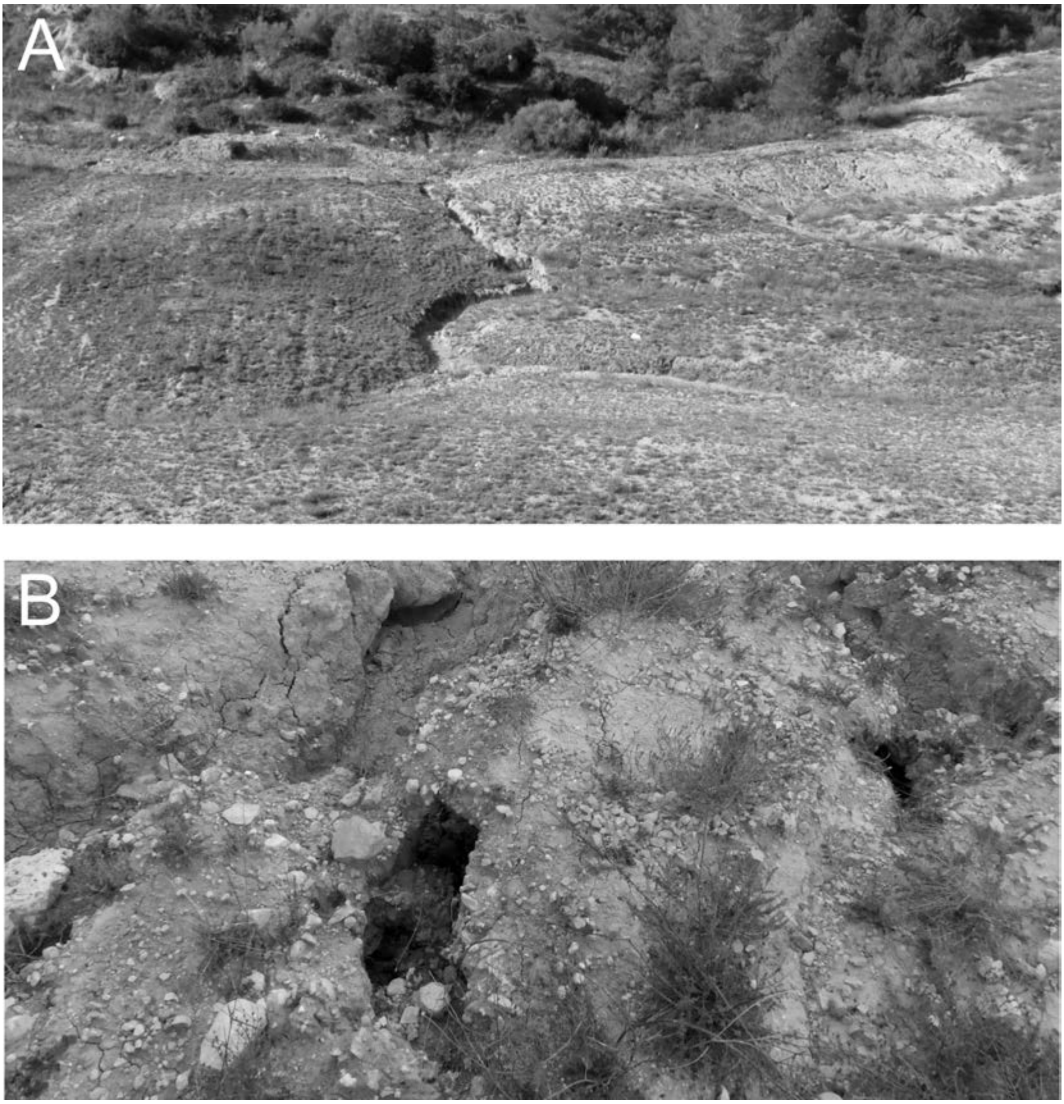

Figure 6. (a) Gully formed from run-on entering from an access road. (b) Tunnel erosion (piping) occurrence related with inappropriate topsoil covering.

GeoFluv – Natural Regrade. Further research in the area should complete a reference characterisation of the hillslope and fluvial systems *(ramblas)* at nearby scenarios, to incorporate their morphometric outcomes in the designs.

4.3. Learned lessons from Aurora

As demonstrated through 4-years monitoring of Aurora, a stable landscape integrated with the surroundings was created. Field work inspections show approximate balances among erosive forces and resistances [13]. The Aurora restoration implementation and monitoring allowed useful learning lessons, to be considered for future mine projects in the region, with some being universally applicable. They are:

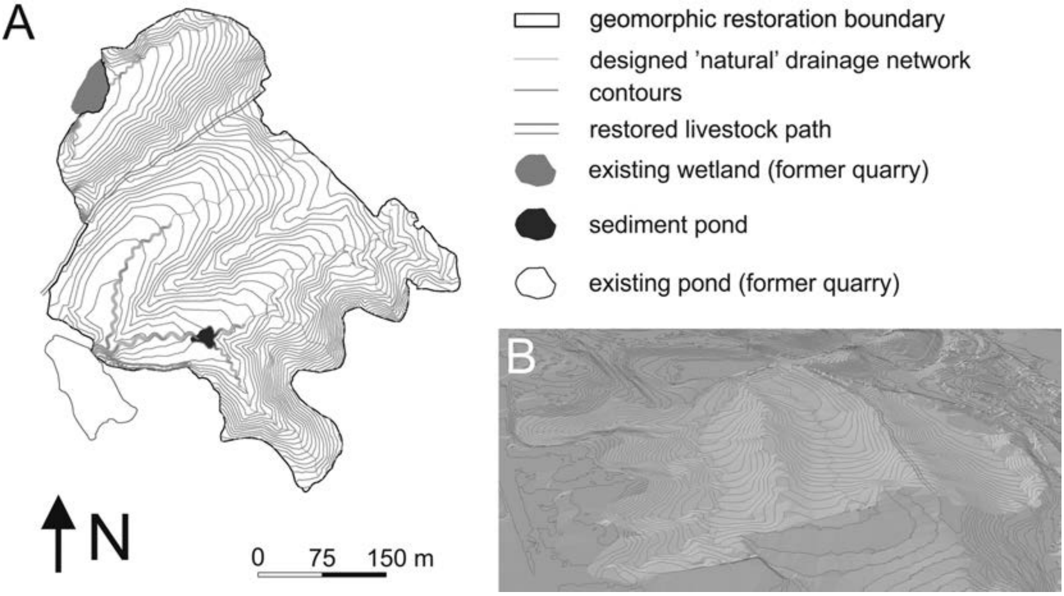

Figure 7. (a) Geomorphic design of Pastor II. (b) 3D view of the design.

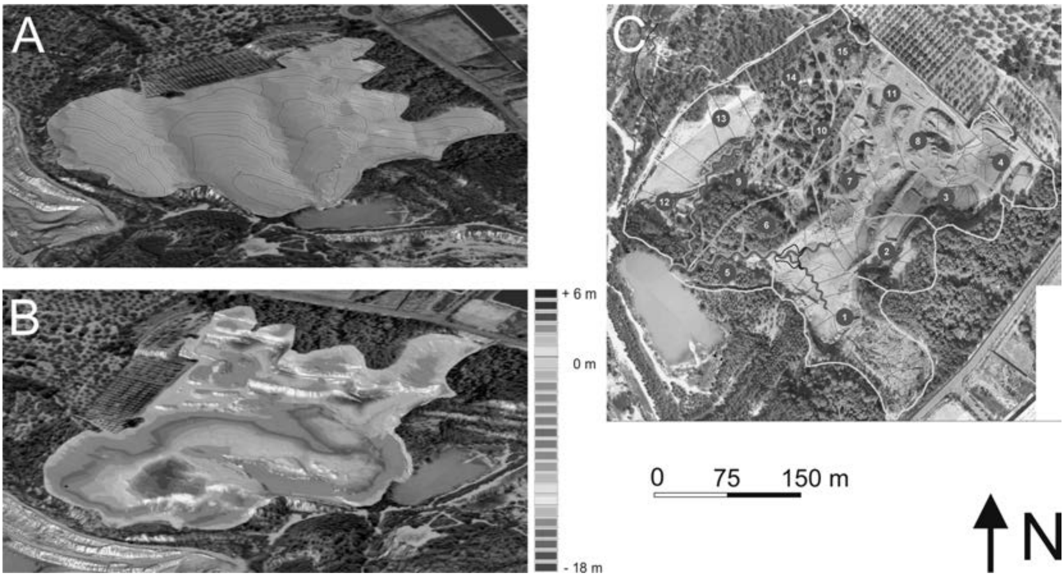

Figure 8. (a) 3D view of the geomorphic design on orthophoto. (b) Cut and fill depths of the final-designed topography compared with the existing one (1-m categories). (c) Staged exploitation-restoration plan for Pastor II. Red lines are either main ridges (curved) or subridges (straight) and blue lines are either fluvial channels (meandering or zig-zag) or swales (straight). Each number identifies a polygon (yellow lines) which is always delimited by ridges, subridges and fluvial channels, so that when constructed, they do not receive runoff from unreclaimed areas. The exploitation-restoration of polygon 1, an independent watershed (see Figure 9(b)) was completed in January 2020. The ortophoto below the lines shows how several staged polygons had been already partially exploited before the new plan, but they were integrated in the geomorphic plan. Source: OFTECO.

- Pre-Existing high and steep benched highwalls, with very limited potential for a setback regrading (because those lands had different owners) were a main constraint to implement geomorphic restoration of them. Indeed, theoretically, geomorphic design can always make

Table 3. Earth movement involved in the progressive geomorphic-based exploitation – restoration at the Pastor II quarry (main watershed). The exploitation-restoration areas are planned according to the final geomorphic restoration design. Exploitation-restoration area 1 has been already completed (see Figure 9). These volumes do not include topsoiling. Source: OFTECO.

STAGED AREA (*)	AREA (m^2)	CUT (m^3)	FILL (m^3)	BALANCE CUT – FILL
1	17,067	13,310	6,961	6,349
2	9,616	10,108	6,105	4,003
3	8,776	8,173	9,436	−1,263
4	7,902	7,787	3,495	4,292
5	4,182	14,558	195	14,363
6	7,635	56,727	0	56,727
7	6,495	24,871	429	24,442
8	5,667	13,633	462	13,171
9	8,907	87,896	0	87,896
10	6,642	49,260	271	48,989
11	4,794	5,648	435	5,213
12	8,497	42,887	0	42,887
13	7,536	66,117	0	66,117
14	6,197	70,843	0	70,843
15	5,161	22,804	35	22,769
TOTAL	**115,074**	**494,622**	**27,824**	**466,798**

stable, functional landforms that are consistent with and honour the local earth materials and climate. But in the Aurora and Pastor I cases, the irresolvable limiting factor was the impossibility of setback regrading. Therefore, their landscape integration and stability of its highwall was limited.

- The highest factor of erosional instability has been upslope run-on entering restored areas not designed to accept it. This happened at the highwall area and from access roads for vegetation maintenance and watering, leading to scattered downslope rilling and gullying. Although this is a well-known situation elsewhere [8], here it was clearly confirmed. Therefore, road drainage should be carefully handled in other mine restoration projects.
- The restored fluvial channels of Aurora, which replicated natural drainage according to the Rosgen’s classification, experienced a relative high channel dynamics, with significant sediment movement. Without a proper geomorphic understanding of the torrential dynamics of the ‘natural’ fluvial networks of this Mediterranean region, this fact could be considered a sign of ‘instability’. Natural fluvial geomorphic landforms are dynamic systems, not static, and the ‘stability’ we seek in restoration must honour the local conditions. The observed dynamics of the Aurora fluvial channels attain the advantages and considerations that Sawatsky and Beckstead (see [10]), masterfully gathered for designing and building drainage networks that replicate natural ones. They are: (a) the meandering channels attenuated the inflows by providing flood storage, reducing flow velocities; (b) overtopping was avoided by channels located in swales and at the bottom of valleys; (c) instead of rigid bed and banks (such as of concrete or rip-rap), the designed channels had a natural armour mobile bed to move in response to extreme flood events; (d) these ‘natural’ replicated channels were able to move vertically in response to changes in the river system; (e) large floods on channel beds washed out their formed armour layers, however, subsequent flows caused bed re-armouring through a resupply of coarse material or by limited degradation of the channel bed. The net result has been the re-establishment of stable local fluvial regimes. Replication of natural channels and systems in Aurora reduced the risk of accelerated erosion and enabled the self-repair of erosion control systems. The observation of the bed re-armouring at Aurora led us to incorporate proper armouring at Pastor II from the beginning (Figure 11) as an extra stability safety measure, once we had visual evidences of worse edaphic conditions at the hillslopes (see reddish colours at Figure 9).

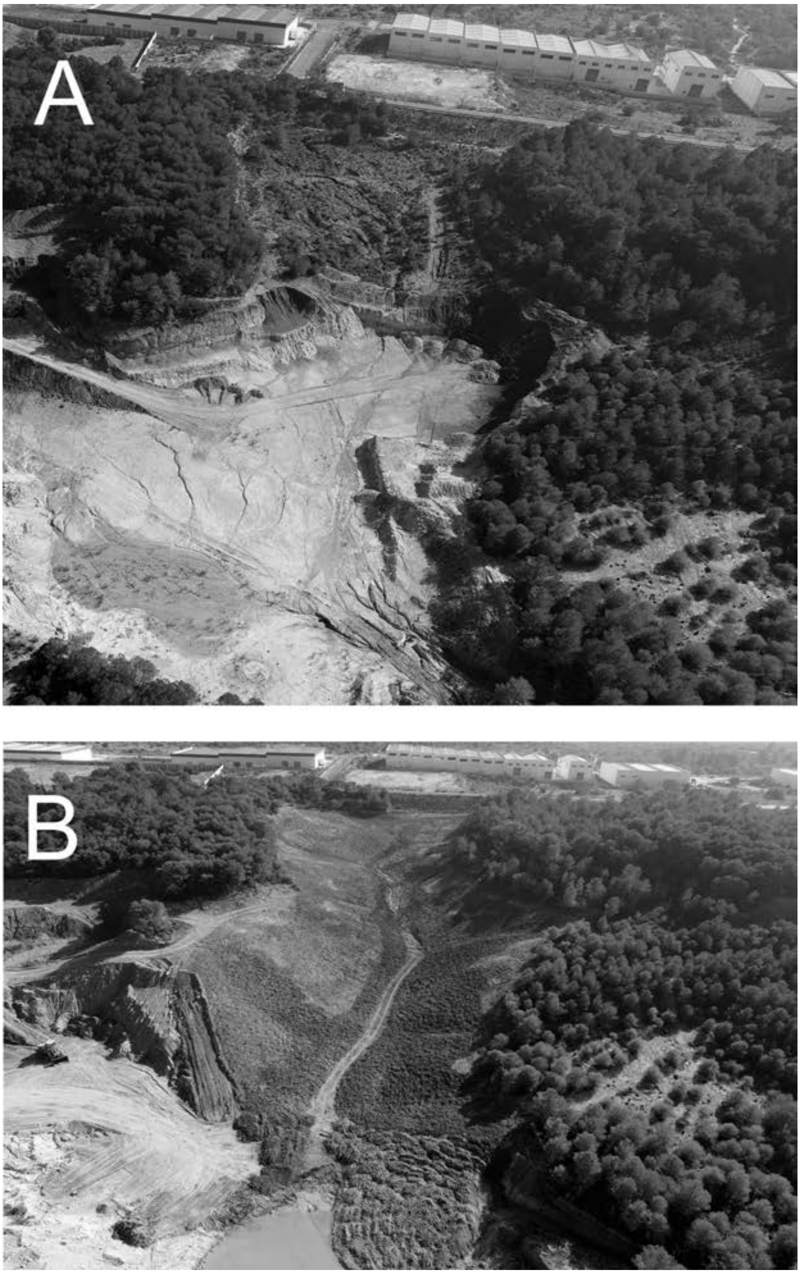

Figure 9. (a) Oblique aerial view of Pastor II – starting point in February 2019. (b) Oblique aerial photo after geomorphic restoration, in January 2020 (both photos by OFTECO). Note the road at the head of the restored watershed for comparison of both photos. Note also that the main channel is not completed yet, which is being used as a road access for revegetation. A detail of its final shape is shown at Figure 11(b).

4.4. Lessons learned from Pastor II

The main constraint to implement geomorphic restoration in this clay quarry setting, the pre-existence of high and steep benched highwall in Aurora, was solved in Pastor II, where the final ridge-and-valley geomorphic landform was able to be incorporated throughout exploitation.

Figure 10. Oblique aerial photos of Pastor I from June 2014, before restoration, end-of-mine state, to May 2020, after restoration (photos by Paisajes Españoles and OFTECO).

The most remarkable contribution of the Pastor II project work is that progressive geomorphic mine restoration is being fully implemented in the mining operations of clay quarrying by CEMEX Spain. The changes from end-of-mine to progressive restoration, and from a traditional (benched highwall with platforms) to a geomorphic approach, have not exhibited any negative economic or operational effects, neither in terms of volume of clay (reserves) nor in the change of machinery pool and operations. The only, but significant difference is to organise the exploitation-restoration process with a different operational plan. This allows the general shape of the restoration landform to emerge as the excavation process progresses as efficient earth movements. This practice has other advantages, such as (a) the design can evolve over the Life-of-Mine (LOM) as performance is assessed; (b) the closure objectives can be met, and bonds can be released, during operations; (c) the evolution of erosion stability and vegetation can be monitored, and strategies optimised, over the LOM. Different from conventional practices, this solution entails a careful plan and strategy in advance, training of the machinery operators and careful progressive topographic staking out. In short, the total earth movement of mining and restoration has been minimised to produce the stable landform and maximise cost savings.

Table 4, modified from the one proposed by Pearce (see [61]), gathers the main advantages learned in Pastor II of both progressive mine restoration, and geomorphic progressive mine restoration, with respect to an end-of-project mine restoration approach.

As a final discussion point, we argue that 4 years of monitoring at Aurora clearly demonstrate landscape advantages by multiple geomorphic-based mine restoration successes. The main benefit is the recovery of hydrologic connectivity, by ‘blending into, and complementing, the drainage

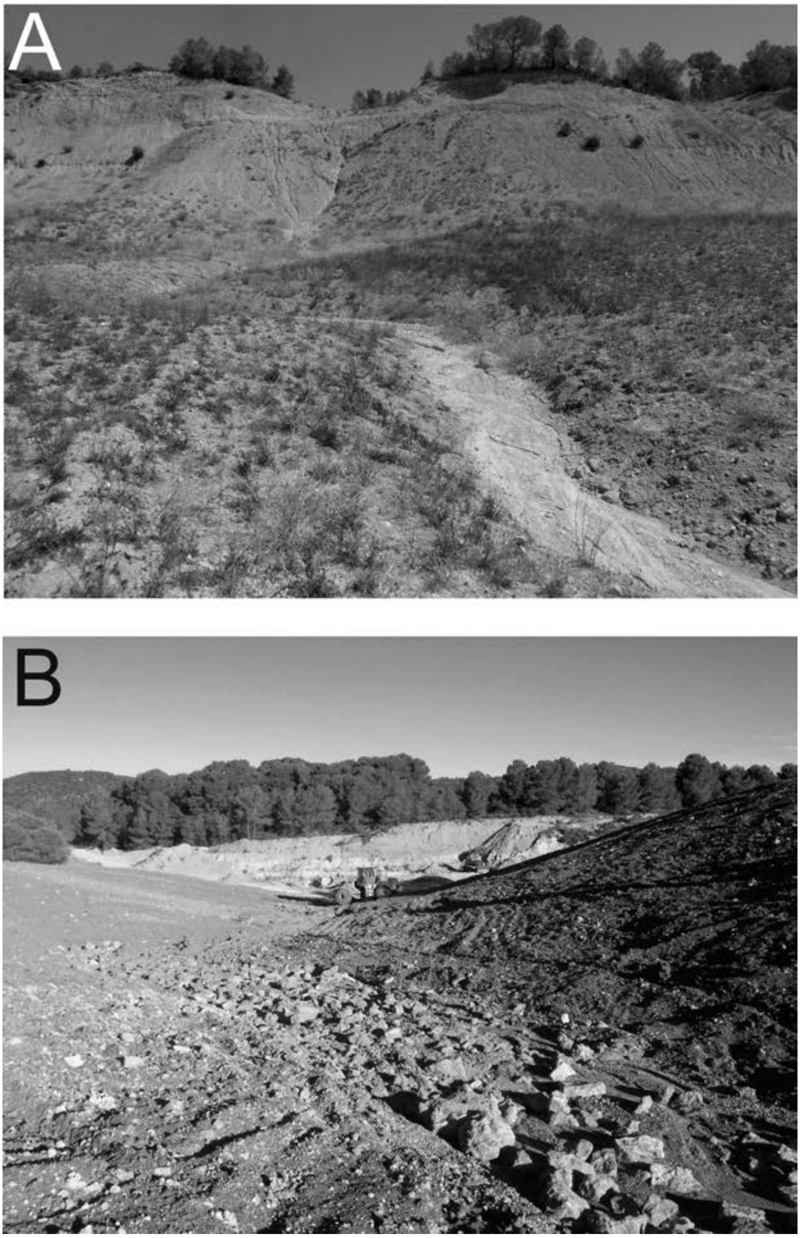

Figure 11. (a) Restored fluvial channel replicating a natural one, at the Aurora restored quarry, after four years of restoration. As it can be seen, the channel is subject to active sediment movement. However, such dynamic is fully integrated in the natural one of this environment, allowing the self-repair of nearby hillslopes. (b) Restored fluvial channel at Pastor II, incorporating extra safety armouring (limestone pebbles and boulders) at the outset.

pattern of the surrounding terrain', in the sense of SMCRA (see [24]). It also augments soil development and habitat recovery with complementary topsoil and revegetation measures. Finally, visual blending with the surroundings is reached (Figures 5 and 9). Replicating geomorphic natural landforms and drainage lines is the basis for such achievements, which allows the opposite reasoning – without a geomorphic approach to repair ecosystems disturbed by earth movements, recovery will be always partial, and should not be termed as either truly 'ecologic' or 'landscape' restoration.

Table 4. Key differences between end of life mine rehabilitation, progressive mine rehabilitation and progressive geomorphic mine restoration (based on Pearce, see [61]).

End of project mine rehabilitation	Progressive mine rehabilitation	Geomorphic progressive mine restoration
Rehabilitation is independent of exploitation. Therefore, any landform design needs to adapt to the final exploitation scenario	Exploitation and rehabilitation are the same process and are coordinated mostly according to conventional landform design (linear topography and engineered drainages)	The general shape of the restoration geomorphic landform emerges as the excavation process progresses. Total earth movement of mining and restoration is minimised to produce the stable landform and maximise cost savings
The wastes are commonly accumulated forming monolithic structures, either outside or inside the exploitation	Staged waste placement	Staged waste placement moved according to the geomorphic design of natural landforms, or restoration plan, with efficient earth moving
Commences after majority of operations finished	Commences during operations	Commences during operations adapted to the final geomorphic landform
Rehabilitation largely independent of mine plan/schedule	Rehabilitation synchronised with mine plan/schedule	Restoration synchronised with mine plan/schedule staged according to geomorphic landforms
Design fixed and performance monitored only after mine closure	Design evolves over the Life-of-Mine (LOM) as performance can be assessed	
Closure objectives and bond released met after operation finished	Closure objectives can be met, and bonds can be released, during operations	
Erosion stability and vegetation only monitored after closure, and therefore, no option of optimisation exists	Evolution of erosion stability and vegetation can be monitored, and strategies optimised, over LOM	

5. Conclusions

The main conclusions obtained from implementing geomorphic-based restoration and the Aurora’s clay quarry landscape monitoring are the following:

- The main constraint to implement geomorphic restoration in this setting has been the pre-existence of high and steep benched highwalls, with limited possibilities of setback regrading due to its proximity to the property boundary.
- The highest factor of erosional instability has been the run-on entering from upslope to restored areas. Poorly planned discharge of road run-off water to reclamation land areas not designed to accept it caused erosional instability.
- Designing and building drainage networks that replicated ‘stable’ natural channels did not imply that channel dynamics have not occurred, including sediment movement. Without a proper geomorphic understanding of the torrential inconstancies of the natural fluvial networks of the region, the described dynamics may be misconstrued as a sign of ‘instability’. However, the changes at the designed drainage channels, which replicate natural ones, are assessed as sustainable steady state regimes, similar to the local *ramblas*, and are considered far superior and stable to conventional-engineered drainage systems.

The most remarkable conclusion of the project work implemented in Pastor II is that progressive geomorphic mine restoration is feasible, and it is being fully implemented in the mining operations of an active clay quarry. The change from end-of-mine to progressive restoration, and change from a traditional (benched highwall with platforms) to geomorphic landforms have not implied any negative effects, neither in terms of mineral volume production nor in the change of machinery pool and operations. The geomorphic landform design and the mining plan complement one another. This technique has undisputed and evident ecological and landscape benefits in balance with quarry productivity.

We believe that the listed conclusions are useful for future mine projects in the region, some of them being universally applicable [62].

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The fluvial geomorphic-based restoration of the Aurora quarry has received four important recognitions, both at Spanish and European levels.

(1) First prize for the Best Available Techniques, Best Operational and Innovative Practices (Economy – Innovation category) of the ANEFA-FdA National Awards for Sustainable Development in Quarries and Gravels (April 2018, Madrid).
(2) Recognition for excellence in the category of Best Practice or Innovation in Recycling, Marine or Manufactured Aggregates at the UEPG *(Union Européenne des Producteurs de Granulats*, or European Aggregates Association) Sustainable Development Awards 2019 (November 2019, Brussels).
(3) Selected by the Spanish Minister of Environment, in its main guide for Ecological Restoration, as best practice for mining ecological restoration, see [62].
(4) Due to the Aurora example, and a few others in Spain, the European Commission has recognised the Geomorphic Restoration among the Best Available Techniques for the Management of Waste of the Extractive Industries. See [44].

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

[1] R.L. Hooke, *On the history of humans as geomorphic agents*, Geology 28 (9) (2000), pp. 843–846. doi:10.1130/0091-7613(2000)28<843:OTHOHA>2.0.CO;2.

[2] R.L. Hooke and J.F. Martín Duque, *Impact of the Great Acceleration in our life-support systems*, in *Treatise on Geomorphology*, J. Schroder, ed., Elsevier, Amsterdam, 2020.

[3] USDI, *US Dept. of Interior*, in *Impact of Surface Mining on Environment, in Man's Impact on Environment*, T. R. Detwyler, ed., McGraw Hill, New York, 1971, pp. 348–369

[4] J.E. Young, *Mining the Earth (Worldwatch Paper 109)*, Worldwatch Institute, Washington DC, 1992.

[5] R.L. Hooke, J.F. Martín Duque, and J. Pedraza, *Land transformation by humans*, GSA Today 22 (12) (2012), pp. 4–10. doi:10.1130/GSAT151A.1.

[6] J.F. Martín Duque, I. Zapico, R. Oyarzun, J.A. López García, and P. Cubas, *A descriptive and quantitative approach regarding erosion and development of landforms on abandoned mine tailings: New insights and environmental implications from SE Spain*, Geomorphology 239 (2015), pp. 1–16. doi:10.1016/j.geomorph.2015.02.035.

[7] M.A. Palmer, E.S. Bernhardt, W.H. Schlesinger, K.N. Eshleman, E. Foufoula-Georgiou, M.S. Hendryx, A. D. Lemly, G.E. Likens, O.L. Loucks, M.E. Power, P.S. White, and P.R. Wilcock, *Mountaintop mining consequences*, Science 327 (5962) (2010), pp. 148–149. doi:10.1126/science.1180543.

[8] J.M. Nicolau, *Trends in topography design and construction in opencast mining reclamation*, Land Degrad Dev 14 (2) (2003), pp. 1–12. doi:10.1002/ldr.548.

[9] C. Martín-Moreno, J.F. Martín Duque, J.M. Nicolau, A. Muñoz, and I. Zapico, *Waste dump erosional landform stability – A critical issue for mountain mining*, Earth Surf. Proc. Land. 43 (7) (2018), pp. 1431–1450. doi:10.1002/esp.4327.

[10] L. Sawatsky and G. Beckstead, *Geomorphic approach for design of sustainable drainage systems for mineland reclamation*, Int. J. Min. Reclam. Env. 10 (3) (1996), pp. 127–129. doi:10.1080/09208119608964815.

[11] M.J. Haigh, *The experimental examination of hill-slope evolution and the reclamation of land disturbed by coal mining*, in *Geography Applied to Practical Problems*, J.H. Johnson, ed., Geo Books, Norwich, 1985, pp. 123–138.

[12] T.J. Toy and J.P. Black, *Topographic reconstruction: The theory and practice*, in *Reclamation of Drastically Disturbed Lands*, R. Barnishel, R. Darmody, and W. Daniels, eds., American Society of Agronomy, Madison, 2000, pp. 41–75.

[13] T.J. Toy and W.R. Chuse, *Topographic reconstruction: A geomorphic approach*, Ecol Eng 24 (1–2) (2005), pp. 29–35. doi:10.1016/j.ecoleng.2004.12.014.

[14] L.F. Sawatsky, D.L. Cooper, E. McRoberts, and H. Ferguson, *Strategies for reclamation of tailings impoundments*, Int J. Min. Reclam. Env. 10 (3) (1996), pp. 131–134. doi:10.1080/09208119608964816.

[15] L.F. Sawatsky, G. Beckstead, and D. Long, *Integrated mine water management planning for environmental protection and mine profitability*, Int J. Min. Reclam. Env. 12 (1) (1998), pp. 37–39. doi:10.1080/09208119808944019.

[16] G.R. Hancock, J.F. Martín Duque, and G. Willgoose, *Mining rehabilitation - using geomorphology to engineer ecologically sustainable landscapes for highly disturbed lands*, Ecol Eng 155 (2020), pp. 105836. doi:10.1016/j.ecoleng.2020.105836.

[17] L. Balaguer, A. Escudero, J.F. Martín-Duque, I. Mola, and J. Aronson, *The historical reference in restoration ecology*: Re-defining a cornerstone concept. Biol. Conserv. 176 (2014), pp. 12–20. doi:10.1016/j.biocon.2014.05.007.

[18] OSMRE Website, *Geomorphic Reclamation*, Office of Surface Mining, Reclamation and Enforcement, US Department of Interior, December 21, 2019. Available at http://www.osmre.gov/programs/tdt/geomorph.shtm.

[19] T. McDonald, G.D. Gann, J. Jonson, and K.W. Dixon, *International Standards for the Practice of Ecological Restoration – Including Principles and Key Concepts*, Society for Ecological Restoration, Washington DC, 2016.

[20] A.D. Bradshaw, *The reclamation of derelict land and the ecology of ecosystems*, in *Restoration Ecology: A Synthetic Approach to Ecological Research*, W.R. Jordan, M.E. Gilpin, and J.D. Aber, eds., Cambridge University Press, Cambridge, 1987, pp. 53–74.

[21] M. Rico, G. Benito, A.G. Salgueiro, A. Díez-Herrero, and H.G. Pereira, *Reported tailings dam failures. A review of the European incidents in the worldwide context*, J. Hazard. Mater 152 (2) (2008), pp. 846–852. doi:10.1016/j.jhazmat.2007.07.050.

[22] S. Pearce, M. Orr, K. Grohs, and J. Pearce, *Progressive rehabilitation — Martabe Gold Mine as a case study*, in *Mine Closure 2016*, A. Fourie and M. Tibbett, eds., Australian Centre for Geomechanics, Perth, 2016, pp. 619–634.

[23] I. McHarg, *Design with Nature*, Natural History Press for the American Museum of Natural History, Garden City, 1969.

[24] SMCRA *Surface Mining Control and Reclamation Act*, Public law, 95–87, Statutes at Large, 91 Stat. 445, Federal Law, United States, Washington DC, 1977.

[25] J.C. Bell, W.L. Daniels, and C.E. Zipper, *The practice of 'approximate original contour' in the Central Appalachians. I. Slope stability and erosion potential*, Landscape Urban Plan 18 (2) (1989), pp. 127–138. doi:10.1016/0169-2046(89)90004-2.

[26] N. Bugosh, *Fluvial geomorphic principles applied to mined land reclamation*, OSM Alternatives to Gradient Terraces Workshop, Office of Surface Mining, Farmington, January 2000.

[27] N. Bugosh, *Innovative reclamation techniques at San Juan Coal Company (or why we are doing our reclamation differently)*, July Rocky Mountain Coal Mining Institute National Meeting, Colorado, Copper Mt., 2003.

[28] D.M. Stiller, G.L. Zimpfer, and M. Bishop, *Application of geomorphic principles to surface mine reclamation in the semiarid West*, J. Soil Water Conserv. (1980), pp. 274–277.

[29] T.J. Toy and R.F. Hadley, *Geomorphology and Reclamation of Disturbed Lands*, Academic Press, London, 1987.

[30] D.L. Rosgen, *A classification of natural rivers*, Catena 22 (3) (1994), pp. 169–199. doi:10.1016/0341-8162(94)90001-9.

[31] D.L. Rosgen, *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, 1996.

[32] N. Bugosh and E. Epp, *Evaluating sediment production from native and fluvial geomorphic reclamation watersheds at La Plata Mine*, Catena 174 (2019), pp. 383–398. doi:10.1016/j.catena.2018.10.048.

[33] NMMMD. *A Method for the Evaluation of Compliance with the Approximate Original Contour Requirements of CSMC RULE 19.8. NMAC*, New Mexico Mining and Minerals Division, Santa Fe, 2010.

[34] L. Sawatsky and A. Beersing, *Configuring mine disturbed landforms for long-term sustainability*, Proceedings of Mine Closure Solutions, 2014, April 26-30, Minas Gerais, Ouro Preto, 2014.

[35] J.C. Hannan, *Mine Rehabilitation, A Handbook for the Coal Mining Industry*, New South Wales Coal Association, Sydney, 1984.

[36] Environment Australia. *Landform Design for Rehabilitation*, Department of the Environment, Canberra, 1998.

[37] C. Waygood, *Adaptative landform design for closure*, in *Mine Closure 2014*, I.M. Weiersbye, A.B. Fourie, M. Tibbett, and K. Mercer, eds., University of the Witwatersrand, Johannesburg, 2014, pp. 1–12.

[38] I. Kelder, C. Waygood, and T. Willis, *Integrating the use of natural analogues and erosion modelling in landform design for closure*, in *Mine Closure 2016*, A. Fourie and M. Tibbett, eds., Australian Centre for Geomechanics, Perth, 2016, pp. 99–106.

[39] H. Lacy, *Mine landforms in Western Australia from dump to landform design: Review, reflect and a future direction*, in *Mine Closure 2019*, A. Fourie and M. Tibbett, eds., Australian Centre for Geomechanics, Perth, 2019, pp. 371–384.

[40] J.F. Martín Duque, J. Pedraza, A. Díez, M.A. Sanz, and R.M. Carrasco, *A geomorphological design for the rehabilitation of an abandoned sand quarry in central Spain*, Landscape Urban Plan 42 (1) (1998), pp. 1–14. doi:10.1016/S0169-2046(98)00070-X.

[41] J.F. Martín Duque, M.A. Sanz, J.M. Bodoque, A. Lucía, and C. Martín-Moreno, *Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes*, Earth Surf. Proc. Land 35 (2010), pp. 531–548.

[42] I. Zapico, J.F. Martín Duque, N. Bugosh, J.B. Laronne, A. Ortega, A. Molina, C. Martín-Moreno, N. Nicolau, and L. Sánchez, *Geomorphic Reclamation for reestablishment of landform stability at a watershed scale in mined sites: The Alto Tajo Natural Park, Spain*, Ecol Eng 111 (2018), pp. 100–116. doi:10.1016/j.ecoleng.2017.11.011.

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

[44] JRC. *Best Available Techniques (BAT) Reference Document for the Management of Waste from the Extractive Industries in Accordance with Directive 2006/21/EC*, Publications Office of the European Union, Luxembourg, 2018.

[45] R.N. Humphries, *A new method for landscaping quarry faces*, Rock Products 80 (1977), pp. 122H–122J.

[46] R.N. Humphries, *Landscaping hard rock quarry faces*, Landscape Design 127 (1979), pp. 34–37.

[47] P.J. Gagen and J. Gunn, *A geomorphological approach to limestone quarry restoration*, in *Geomorphology and Planning*, J. Hooke, ed., Wiley, New York, 1988, pp. 121–142.

[48] J. Gunn, D. Bailey, and P. Gagen, *Landform Replication as A Technique for the Reclamation of Limestone Quarries: A Progress Report*, HMSO, London, 1992.

[49] Génie Géologique Website, *The Talus Royal method*, December 21, 2019. Available at http://www.2g.fr/.

[50] IGME. *Mapa Geológico de España, Escala 1:50.000. 2ª Serie (MAGNA), Tortosa (Hoja 522)*, IGME, Madrid, 1979.

[51] ICONA. *Agresividad de la lluvia en España*, MAPA, Madrid, 1988.

[52] A. Bernatek-Jakiel and J. Poesen, *Subsurface erosion by soil piping: Significance and research needs*, Earth-Sci. Rev. 185 (2018), pp. 1107–1128. doi:10.1016/j.earscirev.2018.08.006.

[53] S. Goldberg, I. Lebron, J.C. Seaman, and D.L. Suarez, *Soil colloidal behaviour*, in *Handbook of Soil Sciences: Properties and Processes*, P.M. Huang, Y. Li, and M.E. Sumner, eds., 2nd, CRC Press, Boca Raton, 2011, pp. 15–1— 15–39.

[54] P. Rengasamy, E. Tavakkoli, and G.K. McDonald, *Exchangable cations and clay dispersion: Net dispersive charge, a new concept for dispersive soil*, Eur. J. Soil Sci. 67 (5) (2016), pp. 659–665. doi:10.1111/ejss.12369.

[55] N. Bugosh, *Can Appalachian mine reclamation be called sustainable using current practices?* Proceedings of Geomorphic Reclamation and Natural Stream Design at Coal Mines: A Technical Interact, OSM, Bristol, 2009, pp. 51–68.

[56] N.M. Kapolka and D.J. Dollhopf, *Effect of slope gradient and plant growth on soil loss on reconstructed steep slopes*, Int J. Min. Reclam. Env. 15 (2) (2001), pp. 86–99. doi:10.1076/ijsm.15.2.86.3416.

[57] G.R. Hancock, J.F. Martín Duque, and G. Willgoose, *Geomorphic design and modelling at catchment scale for best mine rehabilitation – The Drayton mine example (New South Wales, Australia)*, Environ Modell. Softw. 114 (2019), pp. 140–151. doi:10.1016/j.envsoft.2018.12.003.

[58] C.A. Vacher, R.J. Loch, and S.R. Raine. *Identification and Management of Dispersive Mine Spoils*, Australian Centre for Mining Environmental Research, Kenmore, 2004. (Technical Report).

[59] Australian Government. *Mine Rehabilitation, Leading Practice Sustainable Development Program for the Mining Industry*, Commonwealth of Australia, Canberra, 2016.

[60] M.J. Haigh, *Problems in the reclamation of coal-mine disturbed lands in Wales*, Int J. Min. Reclam. Env. 6 (1) (1992), pp. 31–37. doi:10.1080/09208119208944313.

[61] S. Pearce, *Progressive rehabilitation. Case studies of practical implementation*, Creating Value through Closure: Progression beyond Compliance? Seminar Held at the Luleå University of Technology, Sweden, September 24 2019. presentation (unpublished).

[62] I. Mola, A. Sopeña, and R. Torre (eds.), *Guía Práctica de Restauración Ecológica*, Fundación Biodiversidad, Madrid, 2018.