Natural Drainage Basins as Fundamental Units for Mine Closure Planning: Aurora and Pastor I Quarries

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ABSTRACT

The vast majority of the Earth's ice-free land surface has been shaped by fluvial and related slope geomorphic processes. Drainage basins are consequently the most common land surface organization units. Mining operations disrupt this efficient surface structure. Therefore, mine restoration lacking stable drainage basins and networks, "blended into and complementing the drainage pattern of the surrounding terrain" (in the sense of SMCRA 1977), will be always limited. The pre-mine drainage characteristics cannot be replicated, because mining creates irreversible changes in earth physical properties and volumes. However, functional drainage basins and networks, adapted to the new earth material properties, can and should be restored. Dominant current mine restoration practice, typically, either lacks a drainage network or has a deficient, non-natural, drainage design. Extensive literature provides evidence that this is a common reason for mined land reclamation failure. These conventional drainage engineered solutions are not reliable in the long term without guaranteed constant maintenance. Additionally, conventional landform design has low ecological and visual integration with the adjoining landscapes, and is becoming rejected by public and regulators, worldwide. For these reasons, fluvial geomorphic restoration, with a drainage basin approach, is receiving enormous attention. Its origin is the US SMCRA of 1977, followed by scarce but continued literature on the topic from the US, Canada, Australia and Spain. This literature claimed for the need of replicating the patterns and complexity that stable landforms have in natural catchments. However, that option has not been viable until the development of, still few, fluvial geomorphic design methods and software. This contribution summarizes the lessons learned from the application of one of them (GeoFluv-Natural Regrade) in Spain. Although the overall results are truly positive, two issues need attention: the stability of fluvial channels when additional runoff connects with designed channels and the difficulties for implementing the geomorphic designs as planned.

INTRODUCTION

The vast majority of the Earth's ice-free land surface has been shaped by the dynamic geomorphic processes of water flow over sloping terrain. Drainage basins are structures consequently formed as precipitation and subsurface waters collect into an area-shared outlet. The drainage basin is the most fundamental land surface water management planning unit. Mining, a necessary activity for maintaining our society's current life style, inevitably disrupts this structure as vegetation, soils and overburden materials need to be removed. Mining operations alter natural runoff and infiltration processes and in some cases, drainage courses and underground waters are modified or temporarily cut. Additionally, large amounts of wastes are produced and erosion problems may occur on surfaces affected by mining operations and on created waste dumps. Not to mention associated acid mine drainage (AMD) problems. In other words, mining operations deeply and drastically modify previous 'natural' drainage systems.

Mining operations disrupt this efficient surface structure. Therefore, mine restoration lacking stable drainage basins and networks, "blended into and complementing the drainage pattern of the surrounding terrain" (in the sense of SMCRA 1977), will be always inadequate to manage site water runoff. The pre-mine drainage characteristics cannot be replicated, because mining creates irreversible changes in earth physical properties and volumes. However, functional drainage basins and networks, adapted to the new earth material properties, can and should be restored. In fact, the request for landform stability is evident in the mine restoration regulations of different countries (i.e. Australia, Canada, USA, Chile and Spain).

Dominant current mine restoration practice, typically, either lacks a drainage network or has a deficient, non-natural, drainage design. Extensive literature provides evidence that this is a common reason for mined land reclamation failure. These conventional drainage engineered solutions are not reliable in the long term without guaranteed constant maintenance (i.e. Haigh, 1979; Riley, 1995; Kapolka & Dollhopf, 2001; Nicolau, 2003; Hancock et al., 2008; Nyssen & Vermeerch, 2010; Martín Duque et al., 2015, Martín-Moreno et al., 2018). Additionally, conventional landform design has low ecological and visual integration with the adjoining landscapes, and is becoming rejected by public and regulators, worldwide.

For these reasons, fluvial geomorphic restoration, with a drainage basin approach, is receiving enormous attention. Its origin is the US SMCRA of 1977, followed by scarce but continued literature on the topic from the US, Canada, Australia and Spain. This literature claimed for the need of replicating the patterns and complexity that stable landforms have in natural catchments. However, that option has not been viable until the development of, still few, fluvial geomorphic design methods and software. This contribution summarizes the lessons learned from the application of one of them (GeoFluv-Natural Regrade) in Spain. GeoFluv is a method for land restoration based in hillslope and fluvial geomorphic principles, and it has been applied mostly at open pit (surface) mine restoration. GeoFluv allows designing the landforms to which the land would naturally erode under the climatic and physiographic conditions at the site. Natural Regrade is the software that allows users to make these designs in a CAD format (see Bugosh, Martín, & Eckels, 2016).

Specifically, the cases of Aurora and Pastor I quarries are described here. This contribution includes an explanation of the restoration works carried out in each quarry and the monitoring results to date.

STUDY AREA AND CONTEXT

Location and physical environment

The Aurora and Pastor I quarries, property of CEMEX Spain company, are located in north-east Spain, in the Catalonia Region (296593; 4516984, coordinate system UTM-31 N, datum ETRS 1989). Specifically, they are situated in the Tortosa municipality (Tarragona province), in the 'Comarca del Bajo Ebro' (Lower Ebro Region), see Figure 1. Within this area several clay quarries have been exploited since the 1960s. Materials consumed correspond to blue marls and limonites of Neogene Period, Pliocene (IGME, 1979). This mining area is in the vicinity of one of the three areas that make up the 'Plan of Areas of Natural Interest' ('Plan de Espacios de Interés Natural', PEIN, in Spanish) of 'Serres del Cardó-El Boix', and the Ebro Delta Natural Park.

The 'Serres del Cardó-El Boix' landscape is characterized by the particular chromaticity of geologic materials and the morphology rich in unique elements making this area one of a remarkable landscape value. It is worth mentioning the special interest and the good conservation state of the holm oaks and Mediterranean mixed woods. The vegetation in the vicinity of the quarries is composed of an agroforestry mosaic dominated by maquis and garrigue with palmetto (*Chamaerops sp.*) and pine 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 naturalization. The predominant type of soil is the Entisols (Orthent), according to USDA soil taxonomy.

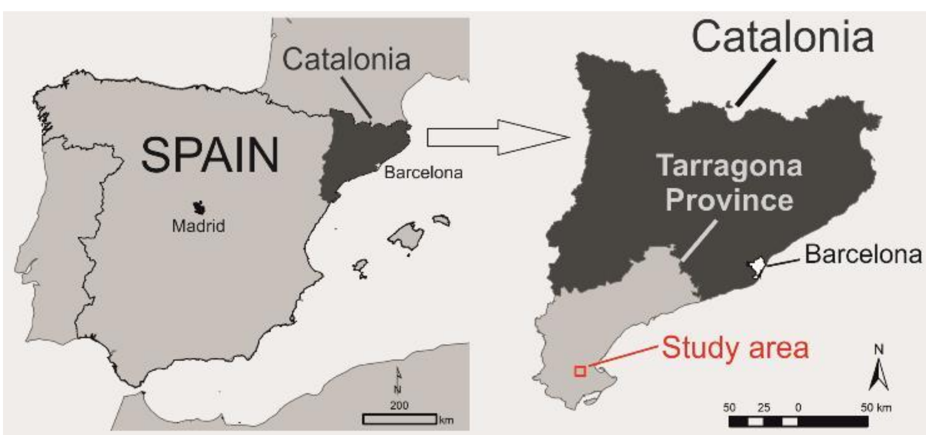

Figure 1 Study area location

The climate of this area is maritime Mediterranean, with mild temperatures (14 ºC of mean annual temperature) and a period of nine months without frost. Mean annual precipitation is 576 mm. The rainiest season is autumn. The water deficit is between 300-400 mm annual mean. The dry period focuses on the summer months. The rainfall erosive factor, R, is estimated to be 185 J m^{-2} cm h^{-1} (Tortosa weather station, ICONA, 1988).

Landscape and drainage network before mining operations

Previous to mining operations, the landscape in this area was dominated by crops and terraces built in the slopes, where olive trees, fruit trees, legumes and cereals were cultivated. By the time, and due to crops abandon, the terraces became deteriorated and crops were progressively colonized by autochthonous species of vegetation. The drainage network was constituted by ephemeral water courses whose hydrology was dominated by lithology (limestones and marls, mainly). Main water courses were, and still being, the Rocacorba and the L'Espluga ephemeral streams with 370 ha and 322 ha watershed area respectively. Other secondary ephemeral water courses, tributaries of these two previously mentioned, also drained the hillslope landscape.

Mining operations in this area altered the natural drainage system. This way, Aurora quarry's operations cut one secondary water course and some water ponds were created by extractive activity, as occurred in Pastor I quarry (see Figure 2).

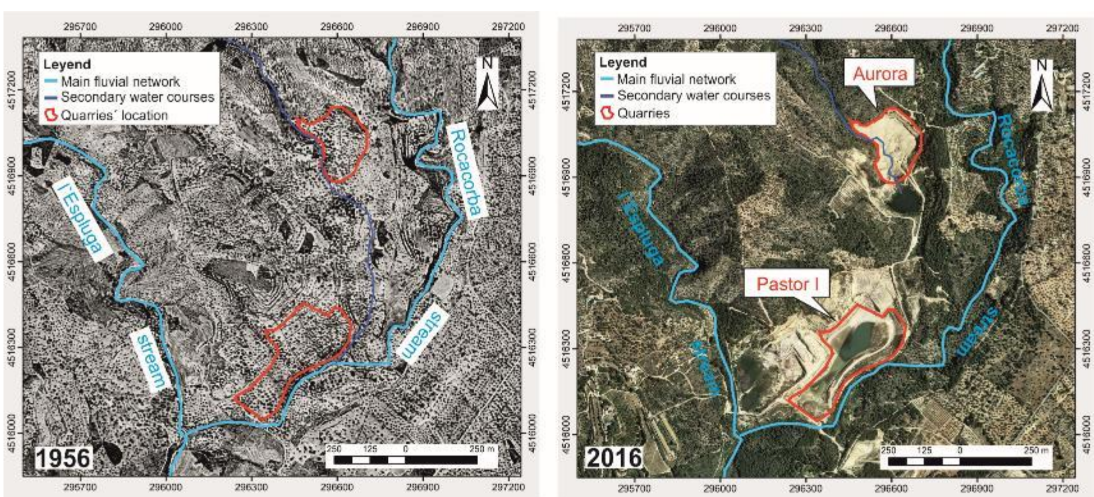

Figure 2 Aerial photos of the study area and main fluvial network in 1956 and 2016. Observe the secondary water course cut by mining operations in Aurora quarry and the created ponds (Coordinate system UTM-31 N, Datum ETRS 1989)

GEOMORPHIC RESTORATION WORKS

In both cases, Aurora and Pastor I quarries, restoration works were focused on apply the geomorphic approach. Particularly, GeoFluv- Natural Regrade method was used to design the new landscapes.

Aurora quarry

The geomorphological restoration, which cover 4 ha, consisted of recovering the hydrological connectivity between an ephemeral stream and a pond, which was interrupted by the extractive activity, as explained before. On the one hand, a drainage network was built, consisting of a main meandering channel, connected upstream and downstream with the natural network (stream and pond, respectively) and three sub-watersheds which connected the natural surroundings with the mean channel by digging small valleys in the highwall. On the other hand, large areas of slopes and hills with gentle slopes have been also built to drain into the channels (see Figure 3). These new landforms were also adapted and connected to a slope previously restored by means of 'conventional' restoration —building rectilinear talus and berms, it is to say terraces—. The design was built between 2014 and 2015.

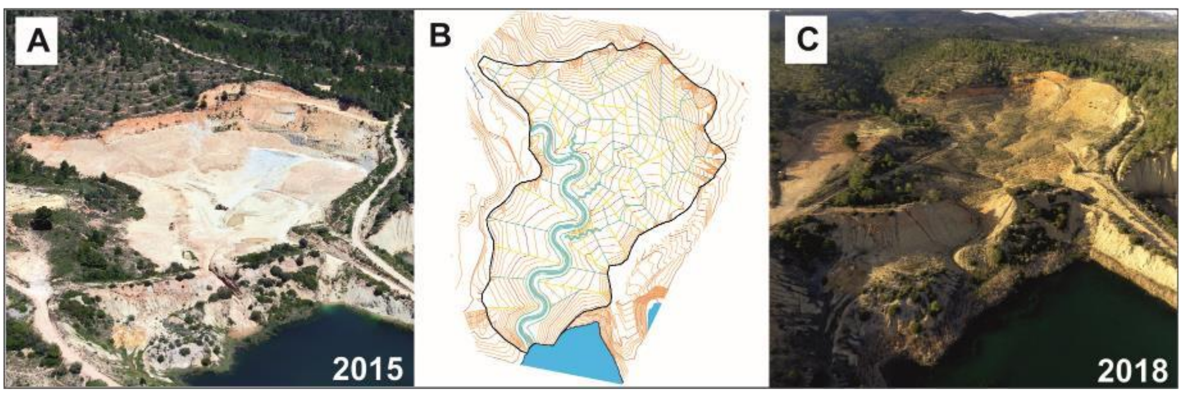

Figure 3 Aurora quarry. A) The quarry during the restoration works, 2015; B) GeoFluv design; C) The quarry in 2018, three years after finishing the restoration

Once the new topography was built, and after the revegetation was carried out, the formation of rills was detected in some areas. This is considered a deviation from what was expected, so the causes of the formation of the rills were studied by direct measurement fieldwork to assess their density and to quantify the volume of eroded sediment. Additionally, the longitudinal profile of design channels and constructed channels were compared to check whether any disconformity with respect to the design occurred.

Pastor I quarry

The objective of the geomorphological restoration here (executed at the beginning of 2018) was to reconstruct the drainage network, and its associated geoforms (GeoFluv design), within the quarry.

This will allow the use of the open pit of Pastor I quarry as a lateral reservoir for the lamination of the Rocacorba stream floods, which cause recurrent floods in agricultural lands downstream. In addition to the GeoFluv geomorphological design (Figure 4), a derivation structure was designed to connect the Rocacorba stream with the reclaimed surface inside the quarry. This structure will be built in the fall of 2018.

To determine the flood flow and the flow rates to be derived, a hydrological study of rain — runoff transformation of the Rocacorba and L'Espluga watersheds was carried out. The watersheds were delimited with ArcGIS software and the study was carried out using HEC-HMS with the Unitary Hydrogram method. In order to dimensionalize the derivation structure, specific hydraulic calculations were carried out in combination with numerical simulation tools through the Iber, a two-dimensional mathematical model for the simulation of free surface flow (Bladé et al., 2014).

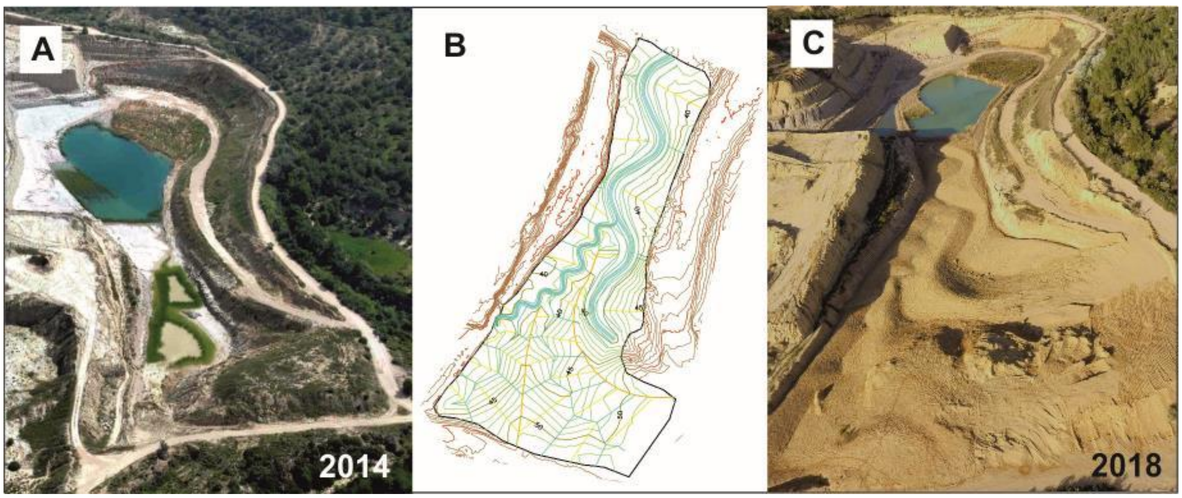

Figure 4 Pastor I quarry. A) The quarry before the restoration, 2014; B) GeoFluv design; C) Appearance of the quarry in 2018, just once the GeoFluv design was built

RESULTS AND DISCUSSION

Aurora quarry

Rill study showed that many rills were generated by uncontrolled runoff from an access road. Some deviations during the construction of the new landforms (absence of concavity) were the cause of rills formation on the slopes adjacent to the margins of the channels. In turn, the areas with the worst soil quality were those with the highest density of rills. Longitudinal profile comparison detected small differences but a stable longitudinal profile was achieved after first rainfall events. Despite this, landforms remain stable and vegetation has perfectly developed.

In short, the drainage network built within Aurora quarry is functional, it allows the controlled evacuation of the runoff generated by the intense rainfall in the area. Additionally it is ecologically and visually integrated with the adjoining landscapes. All of this concludes that the Aurora quarry restoration was worthy of the first prize for the Best Available Techniques and it was selected to the European Awards UEPG 2019 in the FdA National Awards for Sustainable Development in Quarries and Gravels – April 2018, Madrid, Spain.

Pastor I quarry

After carrying out the two hydraulic models, one using all the characteristics of the watersheds and the other incorporating the flood derivation, as well as taking into account the characteristics of the GeoFluv design and the quarry open pit capacity, it was determined that the best corresponding flow derivation were the T50 to T100 return periods. The maximum derived flow will be 10 $m^3 s^{-1}$. The derivation structure was designed through an iterative process, using two-dimensional numerical simulation tools of the water flow incorporating the selected flows and was adapted to the GeoFluv landforms. The derivation structure design will consist of a narrowing in the Rocacorba channel, a smooth depression crossing the road (ford) and a stepped structure down to the open pit (Figure 5).

To date, Pastor I geomorphic restoration has perfectly evacuated to the pond runoff provoked by intense rainfall and any form of erosion has been detected. It is necessary to study GeoFluv design evolution after the derivation structure construction, which will take place on fall 2018.

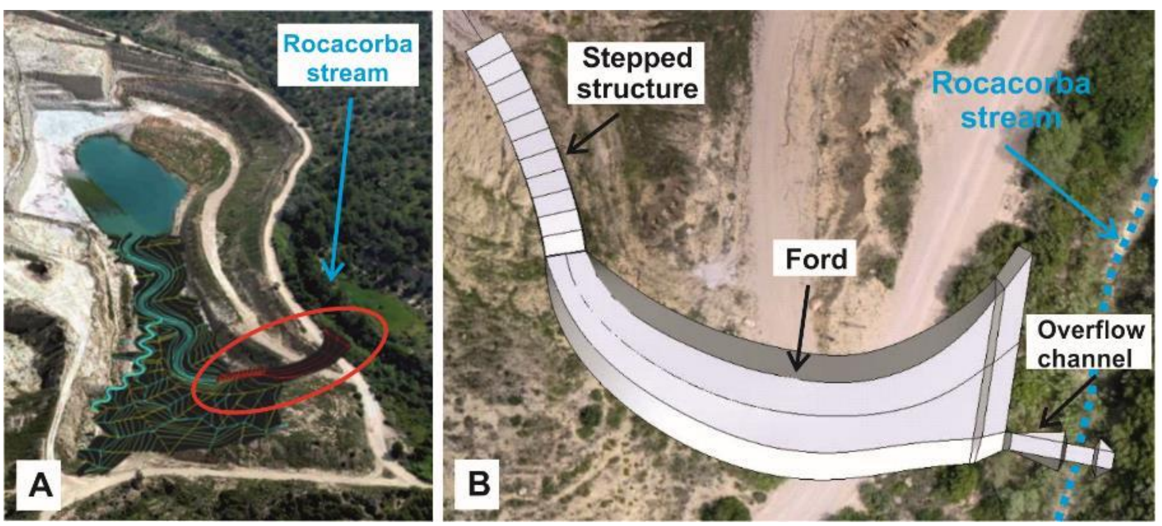

Figure 5 Derivation structure. A) Derivation structure (red circle) adapted to GeoFluv design; B) Derivation structure elements

CONCLUSIONS

The geomorphological restoration approach in mining to include watershed construction, combined with civil engineering techniques, offers solutions that integrate the reduction of natural risks and the ecological restoration. The monitoring carried out in the Aurora quarry shows the importance of carefully reviewing the construction process in order to avoid deviations. The deviations that cause the formation of rills (runoff entries from roads, low soil quality or absence of concavity), will allow improvements to be introduced in future works.

Although the overall results are truly positive, two issues need attention: the stability of fluvial channels when additional runoff connects with designed channels and the difficulties for implementing the geomorphic designs as planned.

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