Ecological Engineering 111 (2018) 100–116

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

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A R T I C L E I N F O

Keywords:
Geomorphic reclamation
Mining reclamation
Landform stability
Sediment yield
GeoFluv
Alto Tajo Natural Park

A B S T R A C T

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

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

1. Introduction

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

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https://doi.org/10.1016/j.ecoleng.2017.11.011
Received 12 April 2017; Received in revised form 5 September 2017; Accepted 13 November 2017
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downstream off-site effects, which can be very detrimental to the environment. Among these, the impact on water quality associated with high sediment loads discharged from mine pits, dumps or facilities to the fluvial system is one of the most harmful (Martín-Moreno et al., 2016; McIntyre et al., 2016; Messina and Biggs, 2016; Zapico et al., 2017). This is worse if acid mine drainage is involved.

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

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

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

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

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

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

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

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

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

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

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