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A descriptive and quantitative approach regarding erosion and development of landforms on abandoned mine tailings: New insights and environmental implications from SE Spain

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ABSTRACT

The San Cristóbal–Perules mining site in Mazarrón in southeast Spain was subjected to about a hundred years of intense mining activity for lead, silver, and zinc. Metallurgical operations (smelting, calcination, gravity concentration) carried out during the late nineteenth century–early twentieth century induced significant land transformation, and the most conspicuous wastes of this period consist of a chaotic piling of 'old' tailing deposits. Later on, during the mid-twentieth century, 'modern' tailings resulting from froth flotation were accumulated filling small valleys; these latter valley-fill tailings rose sequentially according to the upstream construction method, progressively raising the level of the dam during the process. Once abandoned, both types of tailing deposits underwent severe erosion, resulting in a mosaic of erosional and sedimentary landforms developed upon (e.g., gully formation) and within them (e.g., piping). We made an inventory and classification of these landforms. Our study shows the geomorphic work to reestablish a new steady state between the tailings deposits and the local erosive conditions. This scenario implies several hazards related to the extremely high heavy metal contents of these tailings and the geomorphic instability of the deposits. We also quantified the tailings tonnage and erosion that occurred at one of the tailings dams (El Roble). As shown by an oblique aerial photograph taken in 1968, this dam had a terraced topography, whereas in 2013 this morphology had evolved into a badland-type relief with deep parallel gullies. By recognizing and surveying specific, remnant points along the benches and outslopes of the older terraced topography, we were able to build up a first digital elevation model (DEM_1) reflecting the initial topography. A second DEM, this time showing the present topography, allowed quantification of erosion via Material Loss = $DEM_1 - DEM_2$. This yields an erosion rate (1968–2009) of 151.8 Mg (MT) $ha^{-1}\,y^{-1}$, which matches well typical values for erosion of mined areas, commonly above 100 Mg (MT) $ha^{-1}\,y^{-1}$. Abandoned mine tailing deposits are extremely common in the semiarid scenarios of the SW USA, Australia, Chile, and Peru. Given the similarities of these scenarios with SE Spain, the example from Mazarrón may provide useful new insights regarding the erosion and geomorphic evolution of such tailing deposits. These matters should be addressed in key environmental actions such as mine closure plans and land reclamation projects. A solution may come via restoration of these deposits through landform design involving the building up of stable mature landscapes, which in turn can withstand erosion much more easily.

1. Introduction

1.1. Background

Geomorphology is the interdisciplinary and systematic study of landforms and their landscapes as well as the earth surface processes that create and change them (IAG, 2014). Despite that *all* landforms of the Earth's surface are potentially included under that definition, the truth is that geomorphology has traditionally focused on landscapes that have not undergone significant anthropic modification by earth movement. However, the percentage of the Earth's land surface subjected to human modification by earth moving activities has grown significantly in the last decades, and the likely forecast is that it will not stop growing in the forthcoming future (e.g., Rivas et al., 2006; Hooke et al., 2012), as shown by fast-developing countries such as China, India, or Brazil (among others). Humankind has moved and is moving huge amounts of earth thus creating new landforms, a process that often leads to accelerated erosion. The sediments derived from the latter process end up as colluvium on the hillslopes and as alluvium in the floodplains, thus subtly altering the shape of the land. The rest is carried away by streams and rivers. Taking all these matters into consideration, two

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facts must be highlighted: (i) landscapes modified by earth movement activity are becoming a key issue in geomorphology; and (ii) the environmental effects of these new landscapes (runoff from these areas is commonly contaminated and has a high sediment load) and the associated risk potential involving mass movements (flooding, loss of human life, economic catastrophes, etc.) are of paramount importance. This confers to geomorphology (together with environmental geochemistry in the case of abandoned mine sites) a leading role in the understanding of the roots of the problems and in the search for sound closure plans, reclamations and management solutions.

This paper is focused on 'minescapes'—here defined as landscapes generated by mining activity—and in this regard, despite the evident morphological modification that they undergo, most of the research and literature on the subject has focused on geomorphologically based assessments of mining-affected catchments. Langedal (1997) and James (2005) studied the geomorphic implications of dams built to stop fluvial dispersion of tailings. Taylor and Kesterton (2002) researched the dispersal of high metalliferous pollution from spoil heaps derived from copper mining in the Gruben River valley of Namibia. Macklin et al. (2006) showed how the understanding of sediment-associated metal dispersion processes in rivers can be used in a practical way to help river basin managers more effectively control and remediate catchments affected by present and historical metal mining. Lecce and Pavlowsky (2014) assessed the magnitude and distribution of mercury (Hg) and copper (Cu) contamination of floodplain deposits associated with nineteenth century gold (Au) mining activities in the Gold Hill mining district of North Carolina.

Other studies linking geomorphology and mined lands have focused on: (i) criteria for their geomorphic reclamation (Bugosh, 2007); (ii) the application of geomorphic evolution models, under and outside of reclamation measurements (Riley, 1995; Evans and Loch, 1996; Willgoose and Riley, 1998; Evans et al., 2000; Hancock et al., 2003); and (iii) the monitoring of geomorphically reclaimed lands (Martín-Duque et al., 2010). However, very few studies (e.g., Haigh, 1979, 1980) have dealt with actual 'mining geomorphology'. Two examples from Belgium are provided by Nyssen and Vermeerch (2010) and Beullens et al. (2014). The former analyzes the spatial distribution of the main geomorphic processes occurring on coal tips, whereas the second one shows the high impact of slope morphology on the magnitude of rill erosion on coal mine spoil heaps.

1.2. Tailing dams and derived hazards: a brief introduction

The volumes of tailing deposits (creating large new landforms) can be huge; for example, a large mine such as Escondida in Chile is expected to dispose 3.3 billion metric tons of tailings during the period 2003–2043 at its local impoundment facility of Laguna Seca (Chambers et al., 2003). Even relatively small-scale operations may alter the landscape so profoundly as to eliminate an entire bay with its harbor facilities as it happened in Portman (Spain) (Oyarzun et al., 2013), not far from our study area. The Peñarroya Mining and Metallurgical Company disposed at Portman Bay about 60 million tons of tailing materials directly to the Mediterranean Sea between 1957 and 1990; a substantial part of it (12.5 Mt) was dragged back by the sea currents progressively infilling the bay, making the shoreline advance between 500 and 600 m seaward (Manteca et al., 2014) thus creating a massive, physical and chemical environmental impact (Oyarzun et al., 2013).

Tailing dams are one of the most unstable minescapes, resulting in evident hazards. These hazards are chemical (leaching and transport of heavy metals and metalloids) and physical (failure of the dam) or a combination of both. Tailing dams may fail because of many reasons, among them, they are not built to last. In fact, different from civil engineering works such as road or tunnel construction, in mining operations the works are basically designed to endure the mine life cycle and little more. A typical case of dam failure relates to piping that occurs if seepage within or beneath the embankment causes erosion along its flowpath. In this respect, excessive piping may result in local or general failure of the embankment (WISE, 2014). The consequences can be catastrophic if human settlements are located in the vicinity of a tailings dam and may affect large areas if the residues reach a river. A situation of this type can develop even if no dam failure happens; all is required is the strong erosion of the tailings dam and a nearby river, as it happens to be in the case of Mazarrón where massive earth removal has taken place in the last 45 years or so. In this regard, the older a tailings dam is the greater and cumulative become the risks, a fact well exemplified by the high heavy metal contents along the Las Moreras seasonal river, which runs alongside the San Cristóbal–Perules mined site in the Mazarrón district (Oyarzun et al., 2011) (see Figs. 1 and 2). Two previous works on the Mazarrón district (Acosta et al., 2011; Oyarzun et al., 2011) indicate the potential contamination risk associated with the tailing deposits. However, a geomorphological approach (either qualitative or quantitative) is not provided by either of them, and this is the focus of this paper.

1.3. Aims and research questions

Based on detailed field work and topographical quantification carried out at the referred Mazarrón district (Murcia, Spain) (Fig. 1)—one of the classic and oldest Pb–Zn mining sites in Europe—we sought to: (i) make an inventory, classification, description, and interpretation (relating geomorphology and geochemistry) of the landforms existing in the tailings dams; (ii) quantify the tailings tonnage and erosion that occurred at the El Roble dam; (iii) interpret the erosive characteristics of the tailings and its hydrological connectivity as a key factor for environmental effects and risk potential. By providing new insights into these matters, we pursued answering these questions: (i) what are the main geomorphic processes currently acting upon these tailing deposits and mobilizing sediments, and how do they operate?; (ii) what is the magnitude of the erosive process at the tailing dams of this minescape?; and (iii) what is the meaning of the highly erosive character of this minescape and what is its hydrological connectivity framework? From this information, we finally sought to assess alternative, geomorphic-based reclamation strategies, asking ourselves if a geomorphic reclamation approach is applicable for tailing deposits. All that focusing on an environmental geomorphology perspective, a discipline originally defined as the practical use of geomorphology for the solutions of problems where man wishes to transform or to use and change superficial processes (e.g., Panizza, 1996).

2. Regional setting

2.1. Physiography and climate

The physiographic setting of Mazarrón is laid by three sierras (Algarrobo, Las Moreras, and Almenara), with altitudes ranging from 400 to 700 m; and the San Cristóbal–Perules mined site is located at the footslope of the Sierra del Algarrobo, surrounded by small volcanic hills (Fig. 1). These sierras define a horseshoe-shaped sedimentary basin (Mazarrón), opened to the north and slightly inclined to the south. The basin is drained by the *Rambla de Las Moreras*, which receives sediments from the sierras, the basin itself, and in its lower course, from the San Cristóbal–Perules mine site. The mining wastes are located at about 5.5 km from the coast (Fig. 1). The major man-made landforms at this location are the result of metallurgical activities and consist of tailing deposits and rock waste dumps (Fig. 3). However, apart from dirt roads and cuts there are no truly large excavations (e.g., open pits) because mining was mostly underground. *Rambla* is a Spanish term referring to wadi: ephemeral fluvial channels of semiarid and arid areas. These wadis have a flat stream bed with vertical banks. They are dry most of the year and are only functional under torrential rainfall, giving rise to flash floods, and able to move high quantities of bedload, suspended sediment, and dissolved cations and anions.