Update of Hydrological Study and Prediction of Flood Levels pf Acidic Pit Lakes (Tharsis Mines, Spain)

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Abstract

In this work, an update of the hydrological properties of 2 acidic pit lakes in the Tharsis mines (SW Spain) is carried out. The methodology is based on the use of the Digital Terrain Model (MDT), the available orthophotographs and the water balance of the acidic lakes. The pit lakes show the same evolution in water level due to their connections with underground galleries, increasi ng the water level at a rate close to 2.8 m/yr until 2016. The water level will reach hydrological equilibrium due to the increase in the evaporation rate and groundwater flow reduction, which will be below the outflow level.

Keywords: Water Pollution, Sulfides, Abandoned Mines, Pit Lakes

Introduction

Large open pits are generated during mining exploitation. When the mining activity ends, water pumping cessation often produces the creation of pit lakes due to a gradual flooding of the open pits. The water level will increase until it reaches a hydrological equilibrium, when the water inputs are equal to the outputs. The outputs are commonly produced by evaporation from the pit lake, but also by surface or underground discharges. In sulfide mining, the waters stored in pit lakes are generally acidic and contain high concentrations of toxic metals, therefore their release could cause a high environmental impact (Castendyk, 2011; Boehrer *et al.*, 2016). The intense mining activity developed in the Spanish part of the Iberian Pyrite Belt (IPB), one of the largest deposits of polymetallic sulfides worldwide, has left 22 open pits (Sánchez España *et al.*, 2008). Most of these mining lakes contain acidic waters and do not have management or control plans. Some of them have not reached equilibrium and their hydrological connections are not well understood (Sánchez España *et al.*, 2014), therefore, it is important to know its evolution and apply restoration measures if needed.

This problem is especially relevant in the Tharsis mining complex, which is one of the most important exploitations of the IPB. The geology of the area consists of four major south-dipping tectonic units: 1) PQ Group shales and sandstones, 2) massive sulfides and shales, 3) basalt-intruded shales with hydrothermal breccia bodies, and 4) rhyodacite sills that intrude shales. Mining began in Tharsis about 5,000 years ago during the Chalcolithic. After a period of inactivity, mining was restarted during the Tartessian and Roman periods (Gonzalo and Tarín, 1888). Later, there was a long period of low mining activity that continued until 1856, when the mine was rediscovered. Underground mining began mainly by room and pillar works in Filón Norte, Sierra Bullones, Filón Centro, and Filón Sur (Fig. 1). Open pit mining began in 1866 in Filón Norte, and a few years later in Sierra Bullones and Filón Centro (Gonzalo and Tarín, 1888). Mining ceased in Sierra Bullones in 1966 (after 100 years of intense exploitation), while mining in Filón Norte finished at the end of the 1990s. The original sulfide reserves in the Tharsis mine were approximately 133 Mt (Tornos *et al.*, 2009). In the Tharsis mines there are 5 open pits, of which 4 of them are flooded with acid water (Fig.1). In addition, huge amounts of mining wastes are dumped around the mine, affecting an area of 4.13 km^2 (Moreno-González *et al.*, 2020). Acid leachates are generated from these

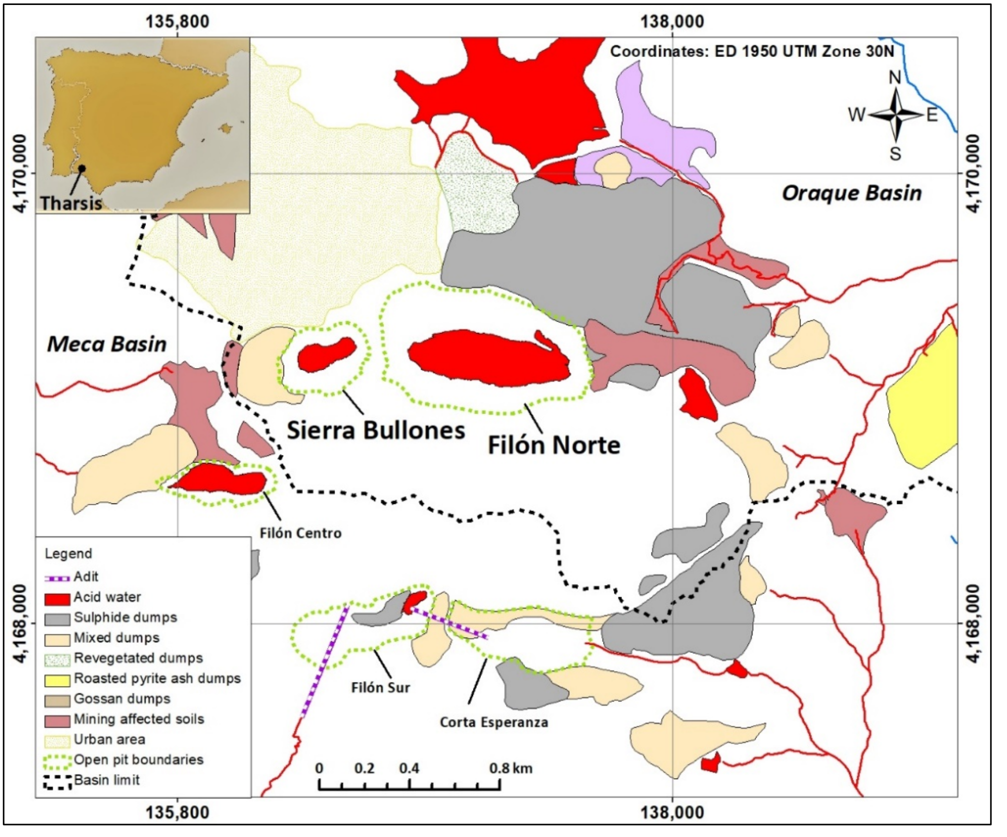

Figure 1 Map of the Tharsis mining district showing open pits, waste dumps and acid streams.

mining wastes that deeply contaminate the water courses in the area (Moreno-González *et al*., 2022).

Currently, there is a project to reopen the mine, which will require the dewatering of the pit lakes and the subsequent treatment of acidic waters previously to its release to the environment. If this project is not carried out, it is essential to know when the overflow level is expected to be reached to apply management plans. An initial estimation was performed a few years ago (Moreno-González *et al*., 2018), however, this could be improved from additional data. Based on the concerns described above, the main objective of this study is to update the available information on the evolution of the water level of the Filón Norte and Sierra Bullones pit lakes, of the Tharsis mining complex, to predict their hydrological evolution.

Methods

In order to determine the evolution of the water level in the Filón Norte and Sierra Bullones open pits, orthophotographs of the National Aerial Orthophotography Plan were used until July 2019. From the flooded surface measured in the orthophotographs and the Digital Terrain Model, it was calculated the elevation of the water level and the volume of water stored (Moreno-González *et al*., 2018).

The daily data on precipitation, temperature, solar radiation and wind speed have been obtained from the La Puebla de Guzmán meteorological station of the Junta de Andalucía, located about 12 km to the west of the Tharsis mine. Daily evaporation was calculated using the Penman equation (1948). The outputs by evaporation were obtained by multiplying the accumulated evaporation in the studied periods by the flooded surface. The direct precipitation on the pit lake

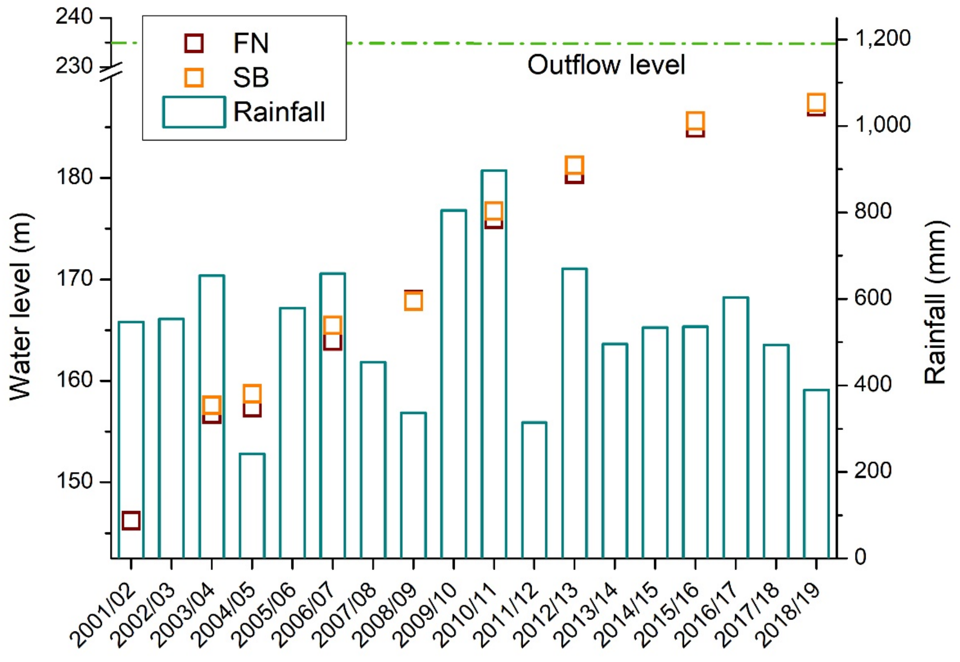

***Figure 2** Evolution of rainfall in the area and water level of the Filón Norte (FN) and Sierra Bullones (SB) pit lakes.*

water surface and the runoff (30% of runoff coefficient) generated in its watershed have been calculated. Finally, the groundwater contributions to the pit lake have been estimated from the water balance; considering the variation in the volume of stored water, evaporation, and surface water inflows.

Results

In the period 2001/22 the average rainfall was 542 mm. The rainiest years were 2009/10 and 2010/11 (maximum of 897 mm; Fig. 2). On the contrary, the driest years were 2004/05 and 2011/12 (minimum value of 242 mm). From 2013/14, there have been several dry years until 2018/2019, except 2016/17 (603 mm). The average annual evaporation obtained by the Penman method is 1,677 mm.

The Filón Norte pit lake began to flood in 2002, increasing at a rate of 2.8 m/yr, until reaching 185 m in July 16 (Fig. 2), following a linear trend (Moreno-Gonzalez *et al.*, 2018). In the same way, the water level of the Sierra Bullones pit lake rose similarly since 2004 to Filón Norte (Fig. 2). This is due to the hydraulic connection between the two pit lakes through underground galleries (Moreno-Gonzalez *et al.*, 2018). In 2019, a growth deceleration of both open pits flooding began to be observed, with an increase of the water level of 2 m from 2016 (this is 0.67 m/yr). The distribution of rainfall influences the changes in the water level of the pit lakes. As mentioned above, in recent years there has been a dry period. In this way, the lower precipitation could contribute to this deceleration in the water level. This deceleration can also be observed in the stored water and the flooded surface (Fig. 3). On the other hand, Filón Norte has higher values of stored water and flooded surface than Sierra Bullones (3.9 x 106 m^3 and 0.135 km^2 in July 2019, respectively), although both pit lakes have a similar evolution.

Figure 4 shows the evolution of surface water inputs (direct rainfall and runoff), evaporation outputs, groundwater inputs/outputs together with the rainfall recorded in each period. Average surface water inputs to Filón Norte were 0.15 x 106 m^3/year, lower than in Sierra Bullones (0.20 x 106 m^3/year). This higher water surface inputs do not agree with the low volume of water stored in Sierra Bullones (Fig. 3), which is 14% of Filón Norte. This is due to groundwater flow from Sierra

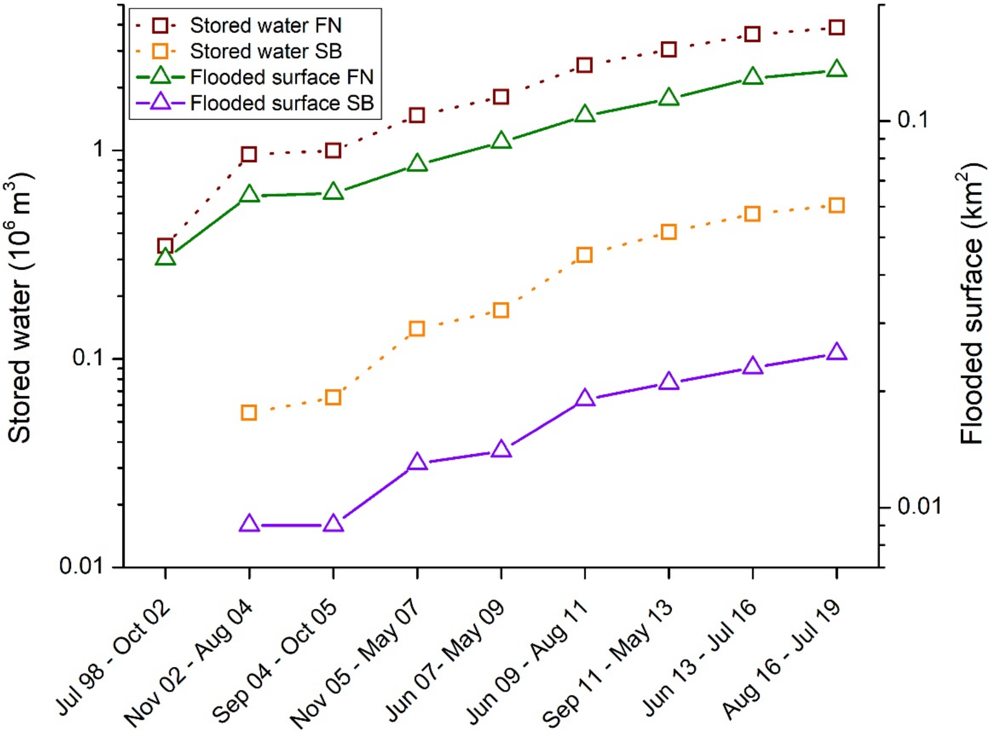

***Figure 3** Evolution of stored water and flooded surface of the Filón Norte and Sierra Bullones pit lakes.*

Bullones to Filón norte through underground galleries. In this way Sierra Bullones behaves as a flow-through pit lake. During the first periods of flooding, the groundwater outputs of Sierra Bullones approximately correspond with the groundwater inputs of the Filón Norte (Fig 3), probably because additional groundwater flows would fill underground mining voids (Moreno-González *et al*., 2018). In the rest of the investigated period, groundwater inputs towards Filón Norte are higher than outputs from Sierra Bullones. In 2019, a reduction in the flow of groundwater towards Filón Norte was observed (Fig. 4), probably due to the drop in the hydraulic gradient induced by the pit lake water level increase (Marinelli and Niccoli, 2000. In addition, evaporation outputs progressively increase as a result of the increase in the flood surface (Fig. 4). Filón Norte and Sierra Bullones would reach equilibrium at 228.5 m, below water outflow level of 235 m (Moreno *et al*., 2018).

Conclusions

The water levels of Filón Norte and Sierra Bullones pit lakes follow a similar evolution after the cease of mining at the end of 1990's, reaching an altitude of 187 m in 2019, although a flooding deceleration is observed in the last years. This trend is also noticed in the stored water and the flooded surface values. The scarcity of rainfalls since 2013, the groundwater flow reductions due to the hydraulic gradient decrease and the increasing evaporation have caused a flood deceleration of the pit lakes, which indicates an equilibrium between inputs and evaporation before reaching the outflow level. Sierra Bullones pit lake behaves as a flow-through pit lake while Filón Norte would be a terminal one. The water level monitoring of the pit lakes should continue to confirm the reduction of the groundwater flow and to observe the effect of rainfall increase once wetter periods take place.

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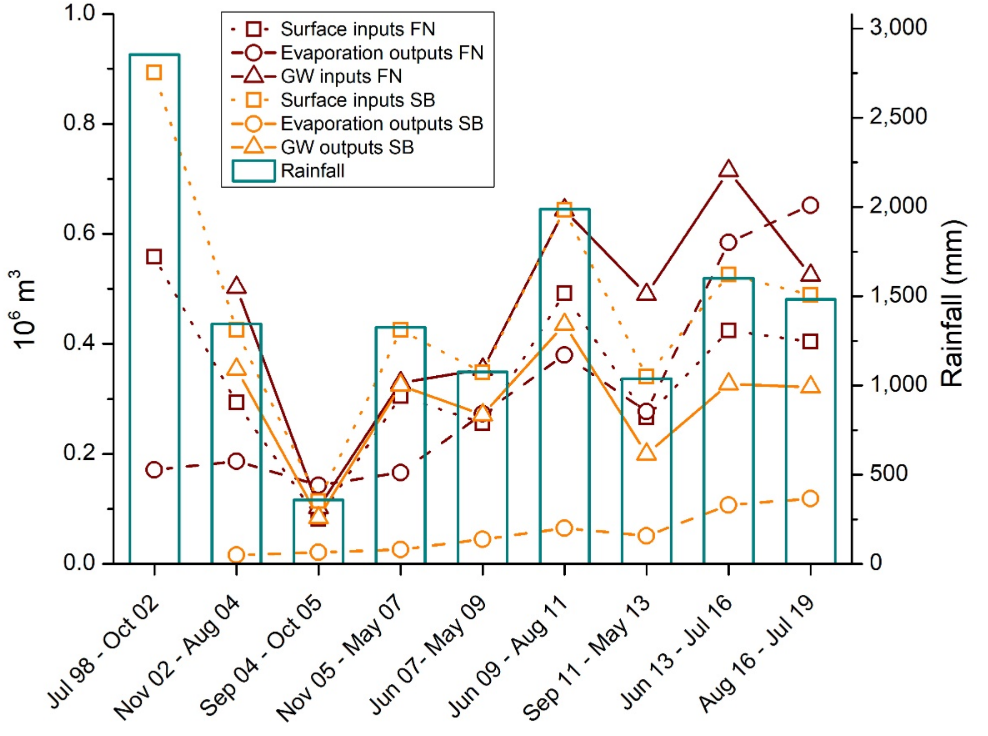

Figure 4 *Evolution of water surface inputs, evaporation outputs, groundwater (GW) inputs/outputs and rainfall of the Filón Norte and Sierra Bullones pit lakes.*

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