Journal of Hydrology 490 (2013) 21–31

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

# The role of surface water and mine groundwater in the chemical stratification of an acidic pit lake (Iberian Pyrite Belt, Spain)

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ARTICLE INFO

*Article history:*
Received 17 October 2012
Received in revised form 28 February 2013
Accepted 13 March 2013
Available online 24 March 2013
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of P.J. Depetris, Associate Editor

*Keywords:*
Mine groundwater
Chemical stratification
Acid mine lake
Meromixis
Chemocline

SUMMARY

The hydraulic system of the Concepción mine is made up of an open pit and an underground mine, which are currently flooded and hydraulically connected. The Concepción pit lake has shown permanent chemical stratification (meromictic lake), where two layers with different density and chemical composition can be differentiated: (i) a thick superficial layer of 11 ± 2 m deep, with a low concentration of dissolved solids (mixolimnion) and (ii) a thin bottom layer from 11 ± 2 m to 16 m deep (monimolimnion), exhibiting vertical changes in its physico-chemical parameters, with decreasing redox potential and increasing T, pH and dissolved solids content with depth. The distribution of the Concepción pit lake layers depends on recharge processes and the loss of water from the system. In winter, rainfall and runoff result in a rapid increase of lake levels. The lake regains its initial level whenever water is lost through an old mine adit, since galleries and shafts act as preferential pathways for inflowing and outflowing water. This network is connected to the bottom of the lake, resulting in the progressive downward movement of the chemocline. Furthermore, runoff generates a less dense superficial layer, which triggers the development of an ephemeral chemocline in the mixolimnion. In summer, the mixolimnion loses water by evaporation which is partially compensated by groundwater inflowing from the lake bottom, resulting in the upward movement of the permanent chemocline. During this period the water level in the system is below the outlet level, which therefore renders the outflow of water inactive. During this stage, the mixolimnion remains homogeneous and the shallow chemocline disappears. Taking into consideration the hydrochemical characteristics of this pit lake and the spatial distribution of the layers identified, a model that explains its seasonal limnological evolution is presented.



## 1. Introduction

Numerous mines that are located along the Iberian Pyrite Belt (IPB) have been exploited both as open pit and underground mines, an aspect that favors hydraulic connection between both systems after flooding. The latter event takes place after pumping ceases, which depresses the piezometric level during periods of mineral extraction.

At present, the Spanish side of the IPB is host to over 30 mine pits that are the result of massive sulfide mining activities. These pits are generally abandoned since no mineral extraction activities (with the exception of Las Cruces) or maintenance activities aimed at preventing flooding are currently taking place, which have resulted in the formation of pit lakes (Lopez-Pamo et al., 2009). Generally, lakes along the IPB are acidic (pH 2–3) with high concentrations of sulfates and metals (Fe, Zn, Cu, Co and Ni) due to the oxidative dissolution of pyrite and other sulfides along with other elements (Al and Mg) that are generated from the dissolution of aluminosilicates in an acidic medium present in the host rock. The size and depth of the lakes are highly variable, depending on the dimensions of the pits and their degree of flooding. Some lakes can reach 100 m depth but most of them show depths between 25 and 50 m.

Eighty-five percentage of mine lakes in the IPB are meromictic (i.e., they exhibit permanent chemical stratification) while the remaining 15% are holomictic (involving a mixing process during the winter that results in the homogenization of lake water). Thermal stratification occurs in all lakes from the beginning of spring through the end of fall. Summer thermal stratification in meromictic lakes increases the intensity of its overall stratification, therefore enhancing the stability of its water column (Sánchez-España et al., 2008; Lopez-Pamo et al., 2009). Several studies have established a relationship between lakes that have low depths and holomictic lakes, as this aspect favors mixing processes during the winter (Levy et al., 1997; Wetzel, 2001). Nonetheless, depth is not the only determining factor known to govern the development of holomixis in lakes (Boehrer and Schultze, 2008). Despite its shallowness, previ-

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http://dx.doi.org/10.1016/j.jhydrol.2013.03.018

ous studies have confirmed that Concepción Lake is a meromictic lake (Lopez-Pamo et al., 2009) since it displays a monimolimnion that occupies the lower third of its water column.

Several works have recently been published which describe the hydrochemistry of the water column in these pit lakes and the limnological processes taking place therein (Santofimia et al., 2007a, 2007b, 2012; Sánchez-España et al., 2008, 2009, 2013; Lopez-Pamo et al., 2009; Díez Ercilla et al., 2009). Despite the build-up of this knowledge, the study of the factors influencing the development of holomixis or meromixis in lakes is far from exhaustive.

The objective of this work is to understand why a pit lake with low depth (16 m) displays a permanent chemical stratification of certain intensity while hosting one of the mixolimnions carrying the lowest amount of dissolved solids in the entire IPB.

## 2. Study site

The Concepción mine, located in the northeast of Huelva province (Iberian Pyrite Belt, Spain) was exploited by underground and opencast mining from 1853 to 1986. Underground mining activities began in 1853 (two floors) using room and pillar methods, reaching a depth of 13 m via opencast mining. In 1874, the opencast exploitation reached the 6th level of the underground mine by means of five banks (Fig. 1). Water was extracted through a tunnel by gravity, which was connected to the 9th floor and had its exit close to Odiel River (Pinedo Vara, 1963) (Fig. 1). Groundwater generated between the 9th and 12th floors was pumped toward this tunnel (ca. 35,000 $m^3$/year). The mine was abandoned in 1986. The tunnel was sealed in the 1990s and caused flooding in the underground mine. The flooding reached the base of the mine pit at a later date 1993 (Checa et al., 2000).

The pit was excavated in a streambed and receives runoff from a basin with a surface area of 0.39 $km^2$. The system comprises the underground mine (shafts and galleries) and the mining pit, which is at present flooded and connected hydraulically (Fig. 1). The pit lake is 280 m long, 60 m wide (equaling a total area 12,000 $m^2$) and has a maximum depth of 16 m. The area of maximum depth is located at the west of lake (Fig. 2).

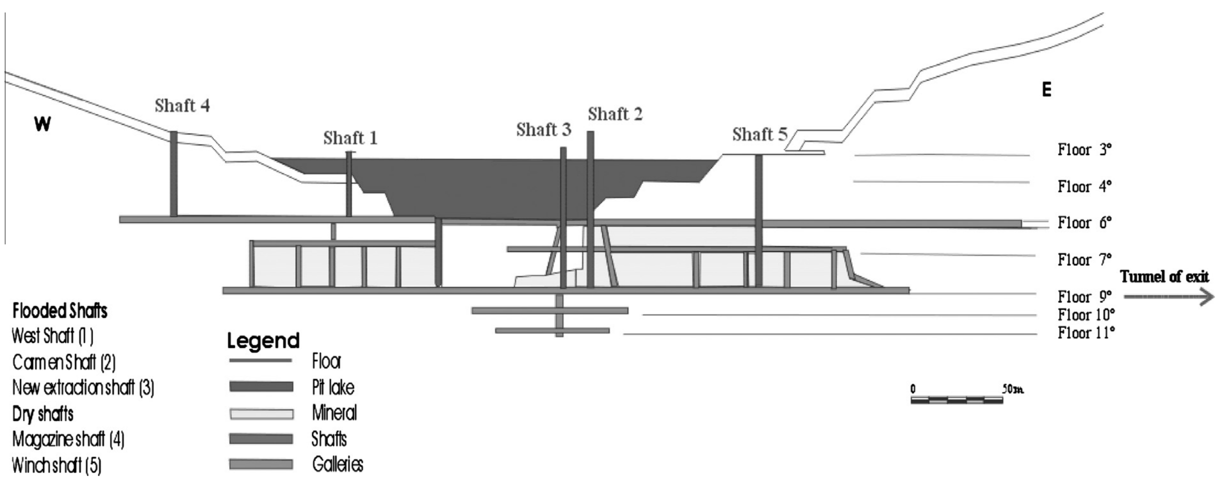


**Fig. 1.** Sketch depicting underground and opencast mining in Concepción mine. Diagram adapted by Pinedo Vara (1963).

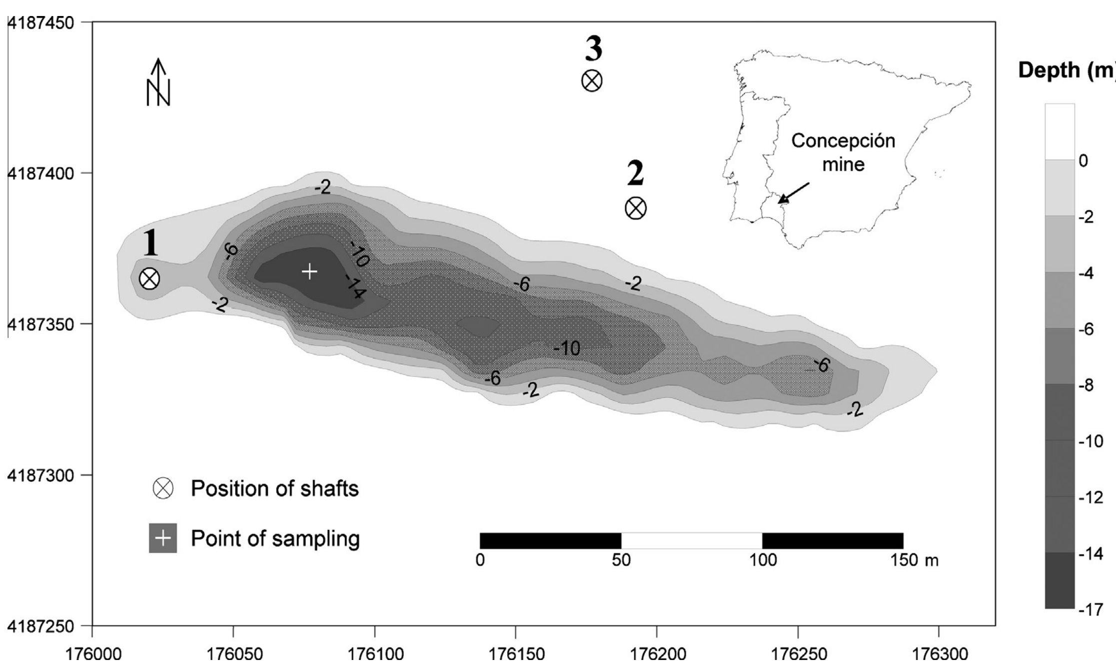


**Fig. 2.** Geographical location and bathymetric map of the mine lake at Concepción mine.