Influence of runoff and groundwater inflow in the stratification developed in the Concepción pit lake (Iberian Pyrite Belt, Spain)

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Abstract The factors that influence the stratification generation of the mining lakes are little known in the lakes developed in the Iberian Pyrite Belt. The mineral reserve of Concepción has been exploited by open pit and underground mining; both systems are currently flooded and connected hydraulically. The Concepción pit lake has shown a permanent chemical stratification (meromictic lake), differentiating two layers with different density: i) a thick superficial layer of ≈ 10.5±1.5 m deep, (mixolimnion), and ii) a thin bottom layer from ≈ 10.5±1.5 m to 16 m deep (monimolimnion). During the hydrologic year 2008—2009 the lake presented two chemoclines: 1) a temporary and shallow (2—4 m deep) that was developed by runoff contribution during intense episodes of rain in winter, and 2) a permanent chemocline, which rose from 12 m in winter to 9 m deep in summer, due to groundwater inflow from shafts and galleries flooded through the lake bottom, counteracting water lost by evaporation. The lake bottom chemistry (the deepest point) is similar to groundwater that floods the shafts. The level variation of the lake (1.05 m) has always been lower at the level variation of permanent chemocline (3 m). This study presents the processes that are involved in the stratification and chemistry of this pit lake, which is meeting place for runoff water and groundwater that floods shafts and galleries of the underground mine.

Key Words Acid mine water, pit lake, meromictic, Iberian Pyrite Belt

Introduction

The Concepción mine, located in the northeast of Huelva province (Iberian Pyrite Belt, Spain), was exploited by underground mining and opencast since 1853. In 1874, the opencast exploitation went up to the 6th floor of the underground mine by means of five banks (fig. 1). Water was extracted through a tunnel by gravity, which was connected with the 9th floor and had its exit close to river Odiel (Pinedo Vara, 1962; fig. 1). Groundwater generated between the 9th and 12th floors was pumped towards this tunnel. The mine was abandoned in 1986. In the 1990s, this tunnel was sealed and caused underground mine flooding to reach the mining pit base, which in 1993 was still not flooded (Checa et al., 2000).

The pit was excavated in a stream bed, therefore it receives runoff from a basin of 0.39 km^2. The system generated by the exploitation is now flooded, so the underground mine (shafts and galleries) as the mining pit, with an hydraulic connection between both (fig. 1). Nowadays, the dimensions of the pit lake are 280 × 60 m and 16 m of depth, with a volume of ≈ 72,500 m^3 (calculated by bathymetric map). The lake level and water level of the shafts are regulated by an exit through

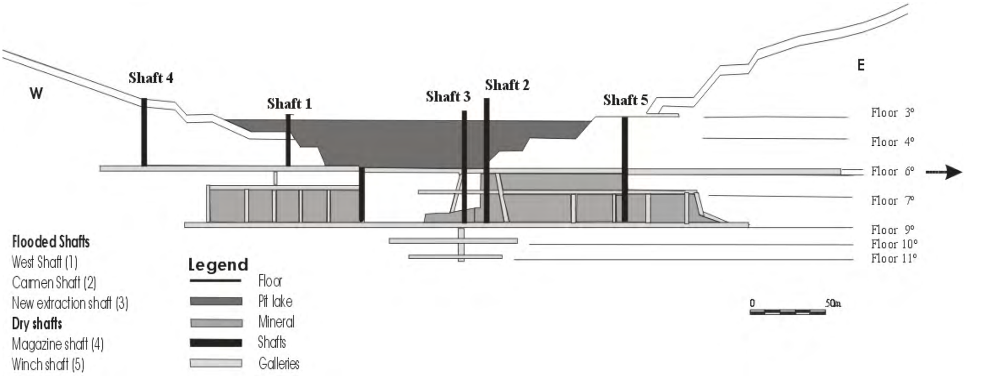

Figure 1 *Underground mining and opencast sketch in Concepción mine (Pinedo Vara, 1962)*

an adit mine (spring), generating acid mine drainage. Groundwater chemistry nature can be studied through three mining shafts. The shaft-1 is located inside of the pit lake. The shaft-2 is situated in the pit slope and the shaft-3 is situated outside of the mine, but both are flooded too (fig. 1).

This study presents the processes that are involved in the stratification and chemistry of this pit lake, such as the inflow of metal-sulphate laden groundwater from shafts and galleries flooded, and the dilution process due to important runoff contributions.

Methods

The field data correspond to several sampling periods conducted between November 2008 and November 2009 (nov-08 and feb-apr-may-aug-oct-nov-09). Depth measurements and vertical profiles of pH, redox potential (Eh), temperature (T), dissolved oxygen (DO), electric conductivity (EC), photosynthetically active radiation (PAR) and chlorophyll-a concentration were collected with a Hydrolab® Datasonde S5 probe from the Hach Company. Additionally, depth measurements and vertical profiles of pH, Eh, T, DO and EC were performed in three shafts with a Hydrolab® Quanta probe. The concentrations of Fe(II) and total Fe were measured by reflectance photometry with a Merck RQflex10 reflectometer and Reflectoquant® analytical strips. Bathymetric was obtained by a Fishfinder Probe 160C model and a GPS 76S model, working in differential mode, both of Garmin. The information was treated with Surfer 8 program. The changes in water levels, during the hydrologic year 2008—2009, were measured by CTD-Diver sensor, and Baro-Diver instrument to compensate barometric pressure data, both of Van Essen Instruments. Daily rainfall data were obtained from the El Campillo climatic station of Andalusian Regional Government, which is located at 10 km southeast of the mine.

Results and discussion

The pit lake is acidic, presenting high concentrations of sulfate and metals (Fe, Al, Zn, Mn and Cu) (López-Pamo et al., 2009). The vertical profiles of physico-chemical parameters (fig. 2) and water chemistry (data not shown) obtained in the Concepción pit lake have shown a permanent chemical stratification (meromictic lake), differentiating two main layers with different density: 1) a thick superficial layer of ≈ 10.5±1.5 m depth, pH 2.5—3, EC 1—2 mS/cm (oxygenated mixolimnion), which represents 90—95% total volume of the lake, and 2) a thin bottom layer from ≈ 10.5±1.5 m to 16 m depth (anoxic monimolimnion), which presents a chemical and thermal gradient with the depth, with pH from 2.5 to 4, EC from 2 to 6 mS/cm (fig. 2) and concentration of Fe from ≈ 100 to 1,000 mg/L (which is as Fe(II)). Between both layers is located a permanent chemocline, which changed its position (in depth) according to an annual cycle.

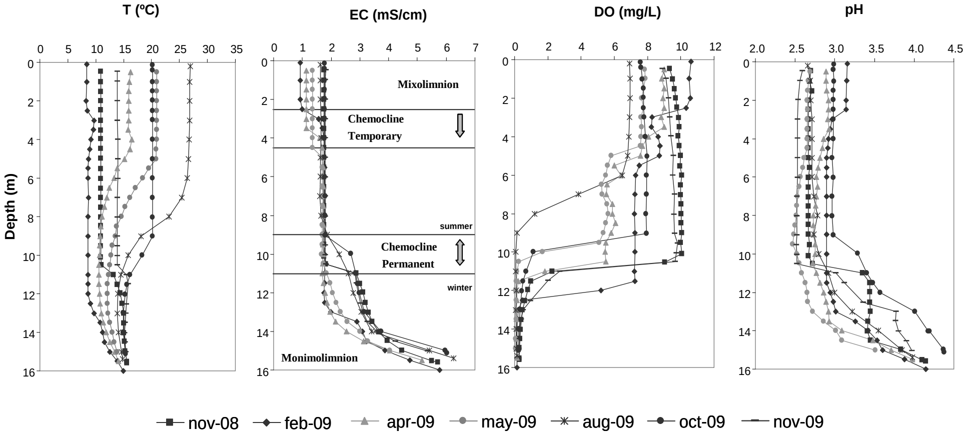

Figure 2 *Depth profiles of temperature (T), electric conductivity (EC), dissolved O_2 (DO) and pH in the pit lake of Concepción*

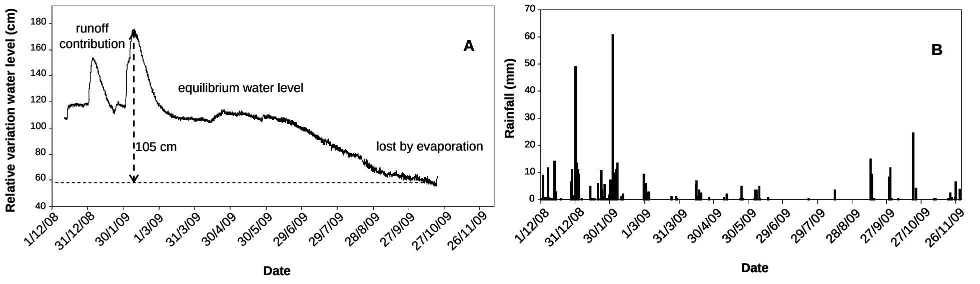

Figure 3 *Daily rainfall (mm) and evolution the lake level (cm) from December 2008 to November 2009 in the Concepción pit lake*

The chemistry of water at the lake bottom is similar to mine groundwater that floods shafts 2 and 3. Theses shafts in depth were anoxic (DO 0 mg/L), presenting low values of redox potential (from 300 to 550 mV) characteristic of ferrous mine water, and concentrations of Fe from 670 to 1,200 mg/L (which was as Fe(II)), pH between 3.3 and 3.5, and an EC between 4.2 and 5.5 mS/cm. The shaft-1 is covered by lake water (≈ 1.5 m thick), whose physico-chemical parameters seem to be the result of mixing between the pit lake and mine groundwater.

In November 2008, a homogeneous mixolimnion (EC 1.7 mS/cm) was shown in the vertical profile (fig. 2), but in February 2009 an upper thin layer (≈ 3 m depth) was recorded with lower EC (0.9 mS/cm). This thin layer was developed by runoff contribution during intense episodes of rain between January and February (rainfall ≈ 220 mm, fig. 3), developing a shallow chemocline (fig. 4A). In this period, the system (pit lake + mine groundwater) was mainly recharged by runoff that arrives at the pit lake (fig. 4A).

From February to May, EC and thickness were gradually increased in the shallow layer due to its mixing with middle layer, caused by wind action. As a result, the EC values of the upper layer were approaching those of the middle layer values and the chemocline moved deeper in the lake (fig. 2). The layers mixture took place despite the development of a thermal stratification that would act to impede this mixing. During recharge of the system by runoff, the water level of the pit lake was increased up to 50 cm (fig. 3A). The lake was returned to its initial level (equilibrium level) in roughly 20 days. This implies that the system has lost a water volume of 6,300 m^3 at the same time, equivalent to a flow of 3—4 L/s. A similar flow to this has been measured in the upwelling (spring), through an old gallery, which is partially demolished (fig. 4A). The spring showed ferrous anoxic water with similar physical and chemical parameters to water in shafts 2 and 3.

The shallow chemocline disappeared in August 2009, due to its complete mixing with a deeper layer due to a density increase, caused in the last months by evapoconcentration. Therefore in February, the mixolimnion stratification was essentially chemical, while in August the

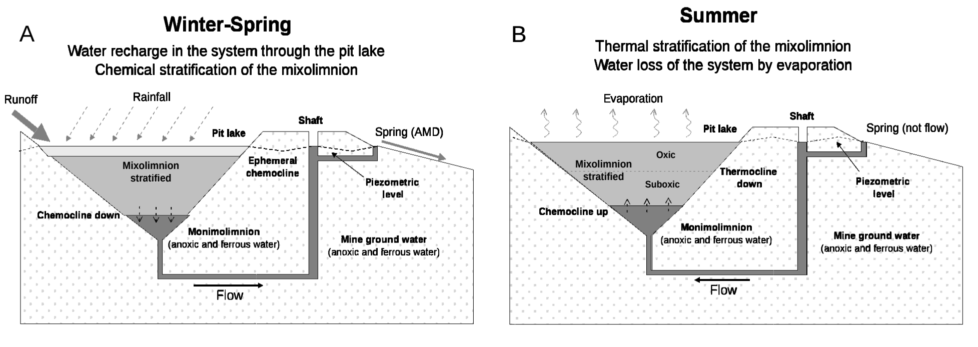

Figure 4 *Mining system sketch. In winter and spring, the system had a water recharge through the pit lake, whereas in summer the system presented water loss by evaporation*

mixolimnion stratification was exclusively thermal. These causes of the layering can explain the DO consumption in the intermediate layer, which was suboxic (fig. 2).

In summer, the mixolimnion presented water loss by evaporation, which was partially compensated by the inflow of groundwater that induced the rise of the permanent chemocline from 12 m (in winter) to 9 m of depth. During this study, the level variations of the lake have been 1.05 m, therefore the chemocline really moved between winter and summer by groundwater inflow, compensating partially the previous water loss in the pit lake. When the system was in equilibrium or had a loss of water (fig. 3A), the water level of the system was below its outlet level, so that the spring in the mine adit was not active (fig. 4 B).

Conclusions

The mine water system is made up of an open pit and an underground mine, which are currently flooded and hydraulically connected. The distribution of the Concepción pit lake layers depends on the processes of recharge and water loss from the system. In winter, the runoff (system recharge) generated a less dense superficial layer, developing an ephemeral chemocline in the mixolimnion. Simultaneously, the mixolimnion was increased in thickness and the permanent chemocline moved down. During the system recharge, the lake level increased. The lake returned to its initial level (equilibrium level) by water loss through an exit (spring), which generated an acid mine drainage. In summer the mixolimnion was homogeneous and the shallow chemocline disappeared. The mixolimnion lost water by evaporation (system water loss), that was partially compensated by inflowing groundwater from the lake bottom, moving upward the permanent chemocline. In this period the water level of the system was below outlet level, the exit being inactive.

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