Water Resources and Hydrogeological Modelling as a Tool for the Feasibility Assessment of the Closure Plan of an Open Pit (La Respina Mine, Spain)

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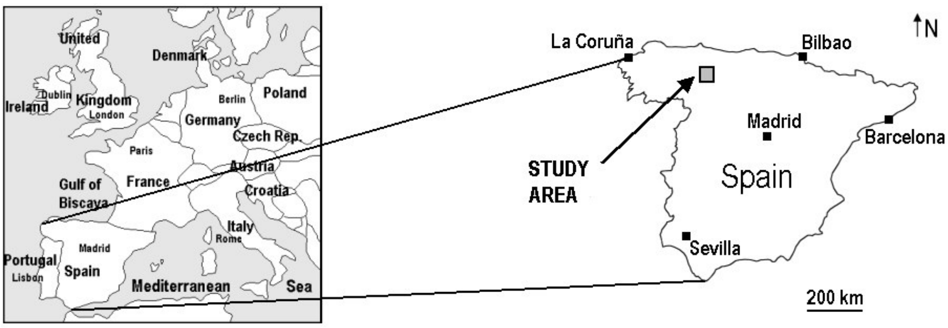
Abstract
La Respina mine is an open pit for talc extraction located in a mountainous range of NW Spain. The closure plan foresees the construction of an artificial lake in the void left by the open pit, which has a total area of 192,945 m^2. The feasibility of the artificial lake has been assessed by means of a daily-based, lumped-water balance, hydrologic model. In this context, the magnitude of the available water resources of the valley has been evaluated, based on the quantification of the different components of the water balance. The results attained are used to estimate the time needed to fill the future lake and to reach the maximum water level, as well as its expected time evolution and associated hydrogeologic impacts.

Key words: La Respina mine, water resources assessment, artificial lake, hydrogeological modelling.

Introduction
La Respina mine is an open pit where talc has been mined since 1930, and it is located in the NW of Spain, province of Léon, on the southern bank of the Cantabric Chain (Figure 1). The open pit is located in the head of a mountainous valley, called La Respina valley, which belongs to the Asturian Carboniferous Central basin. The outcropping formations are composed of Ordovician quartzites and Carboniferous limestones. The formation that is being mined is a Lower Carboniferous limestone that was subject to dolomitisation and subsequent transformation into talc.

Figure 1 *Location of the study area.*



The elevation of La Respina valley is between 1500 and 2000 masl. Its overall hydrogeological functioning is mainly karstic with some areas behaving as porous media, due to local intensification of fracturing and karstification, and also to blasting of talc formations.

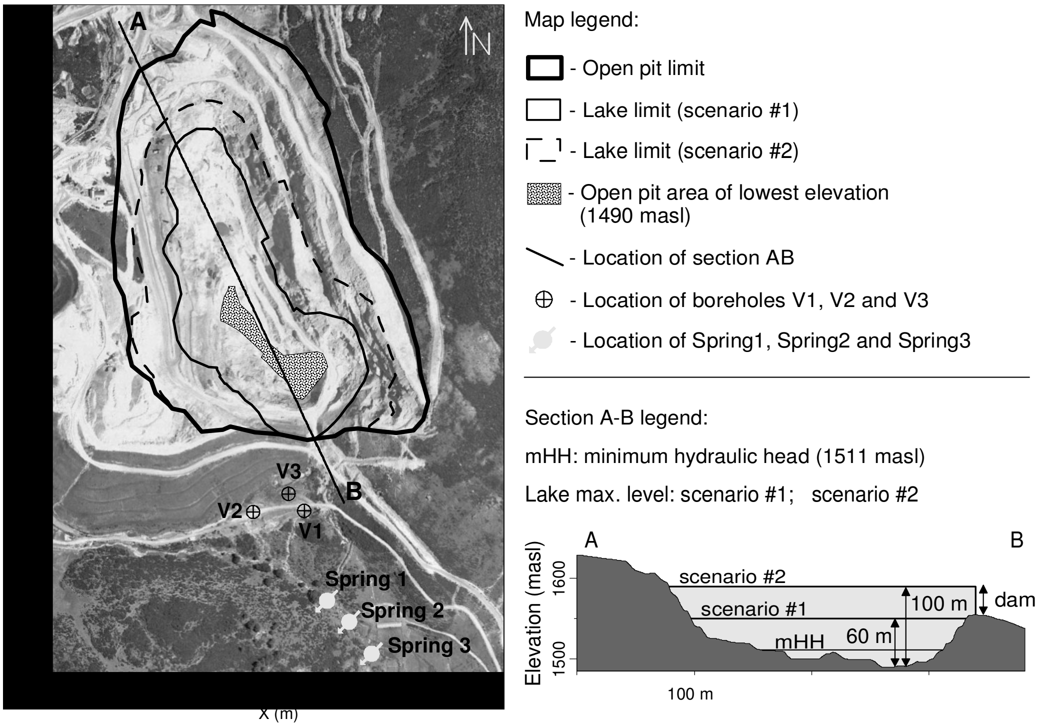
Downstream the open pit there are three springs that were designated, from upstream to downstream, Spring 1, Spring 2, and Spring 3 (Figure 2). Spring 1 and Spring 2 are hydraulically connected to the open pit. Since both springs are mainly fed by the Carboniferous limestones, that are partially karstified, their flow regime is essentially karstic, each with a summer flow between 6 and 10 L/s. Spring 3 shows a much higher and seasonal-constant flow rate of about 300 L/s: it is hydraulically isolated from the open pit, and it is mainly fed by the Ordovician quartzites (Martínez et al. 2006).

The area affected by the talc mining and processing is around 783,000 m^2, with an open pit of 193,000 m^2. The tailings occupy a total area of 411,000 m^2, from which 50% is already reforested.

The closure plan of La Respina mine foresees the generation of an artificial lake in the volume left by the open pit. The definite design of the lake is currently under study. Two alternatives are being studied: one scenario (#1) has a maximum lake water level located 60 m above the open pit bottom (no

dam construction needed), and a second scenario (#2) has a maximum lake water level located 100 m above the open pit bottom, requiring the construction of a dam (Figure 2).
The assessment of the closure plan of La Respina mine is based on (i) the evaluation of water resources of La Respina catchment, (ii) the estimation of the time needed to reach the maximum lake water level and (iii) the prediction of the intra and inter annual variation of the future lake.

***Figure 2** Aerial orthophotograph of La Respina mine, showing the limits of the open pit and future lake. Section of the open pit showing elevation of the minimum hydraulic head and the future lake maximum water level.*



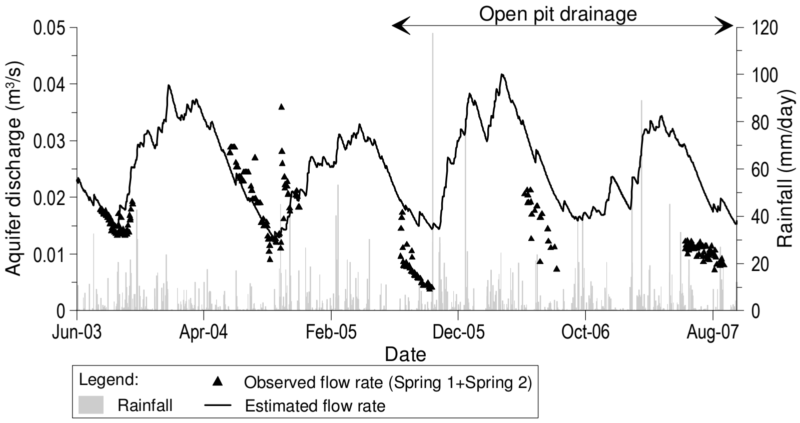
Methods

The evaluation of water resources in La Respina valley is based on its daily based water budget which was developed using the program Visual Balan v.1.0 (Samper et al. 1999). The hydrologic model takes into account the daily rainfall, snow precipitation and snow melt as water inputs into the system. Surface runoff, evapotranspiration, unsaturated zone infiltration and groundwater flow are computed afterwards in a sequential manner. Theoretical details of the applied methodology can be found in Samper et al. (1999). The hydrologic model that simulates La Respina valley water budget was calibrated by comparing computed hydraulic heads and spring flows with a field-collected database.
The estimation of the time needed to reach the maximum lake water level is based on the quantification of the future lake volume and the evaluation of water influxes and outfluxes of the future lake, evaluated in a hydrogeological model that accounts for variable saturated flow. The prediction of the intra and inter annual variation of the future lake is made through the analysis of distinct hydrologic years that characterize La Respina valley and their simulation in the hydrogeologic numerical model.

Results and discussion

The hydrologic model developed for La Respina valley is based on the calibration of snow melt coefficient, aquifer depletion constant, edaphic soil porosity and unsaturated zone characteristic curve, which represent the most uncertain parameters of the studied catchment.
During the years 2003 and 2004, the hydrologic model estimation is very close to the observed flow rates (Figure 3). And, in the years 2005 to 2007 the estimated flow rate is overestimated. In this period the open pit has been drained, and since the hydrologic model does not account for aquifer abstraction, the estimated flow rate corresponds to the flow rate that would be observed if no drainage occurred.

__Figure 3__ Comparison between estimated flow rate for the sum of springs 1 and 2, and the observed values. Model calibration was developed only for the period before the open pit drainage.



The mean yearly rainfall at La Respina valley amounts to 955.6 mm/yr (Figure 4). According to the results of the hydrological model, on an annual basis 56.6% of the precipitation turns into surface runoff, 19.0% infiltrates and recharges the aquifer, and 24.3% is released back into the atmosphere through actual evapotranspiration (ET). The lateral shallow subsurface flow (also named hypodermic flow) represents only 0.2% of the annual rainfall, reflecting the steep slopes that characterize the topography of La Respina valley and which both trigger a considerable runoff and limit lateral flow, as well as the relatively deep groundwater table that favours vertical infiltration. The mean potential evaporation from the lake surface, estimated using the Penman method, is 777.8 mm/yr.

The design of the future lake has been assessed through the evaluation of two scenarios. Regarding scenario #1, the volume of the future lake is expected to be 1.94 Mm^3, with a free water surface of 66,170 m^2, while in scenario #2 it is expected a volume of 5.75 Mm^3, with a free water surface of 123,650 m^2. The maximum lake water column is expected to be 60 m in scenario #1, and 100 m in scenario #2. It is seen that scenario #2 will induce a much larger free water surface, covering a larger area of the open pit, which may lead to a better landscape design. Nevertheless, scenario #2 involves the construction of a dam in the lower part of the open pit border (see Figure 2), which increase the costs involved in the closure plan.

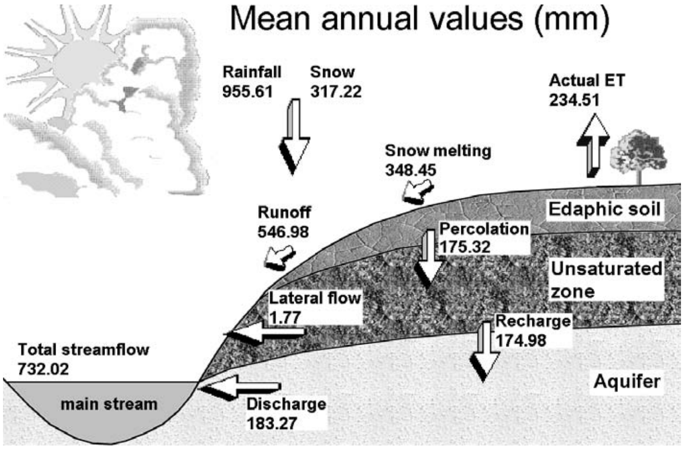
From the attained water budget (Figure 4) it is seen that the inflows to the future lake are: (1) direct rainfall; (2) direct snow; (3) direct snow melt; (4) runoff; (5) lateral flow; and (6) aquifer discharge. The outflows from the future lake are: (1) evaporation; and (2) infiltration. All the lake inflows are outputs of the hydrologic model that has been developed, and therefore their estimation depends on the calibration which is subjected to some degree of uncertainty.

The study of the hydraulic heads of the rock massif that surrounds the open pit permitted the identification of a natural hydraulic gradient of 0.064±0.008 that dips to the south, approximately parallel to the axis of La Respina valley. The hydraulic heads registered in the years 2003 and 2004 in the piezometers located in the open pit reveal a minimum hydraulic head of 1511 masl, which means that the lowest 0.23 Mm^3 of the future lake will be guaranteed by aquifer discharge, and the remainder will be fed by the identified lake inflows.

From the hydrological model outputs it is possible to estimate the mean annual water increment in the future lake, by multiplying the mean specific flows 1, 2 and 3 by the lake free water surface, and the mean specific flows 4 and 5 by the lake catchment area. The annual outflow from the lake, through evaporation, is obtained by multiplying the mean specific flow of 777.8 mm/yr by the lake free water surface.

In scenario #1, the lake volume above the hydraulic head is 1.71 Mm^3, and the mean annual water increment computed from available water resources is 2.19 Mm^3/yr, meaning that in approximately 9 months, the lake maximum water level will be reached. In scenario #2, the lake volume above the hydraulic head is 5.52 Mm^3, and the computed mean annual water increment is 2.21 Mm^3/yr, meaning that in approximately 2.5 years the lake maximum water level will be reached.

Figure 4 *Mean annual water budget (in mm/year) of la Respina valley calculated using Visual Balan v.2.0 (Samper et al. 1999). The results show that, besides rainfall, snow is an important inflow to the overall water budget, and that runoff is the most important flux between the topographic surface and the surface water bodies. Aquifer recharge and real ET represent approximately 22% of rainfall, each.*



Conclusions

The evaluation of water resources in La Respina valley led to the conclusion that in a typically mountainous, high elevation valley, besides rainfall, snow and snow melt are important inflows to the overall water budget. These inflows will contribute to the filling of the future lake, which main inflow will be surface runoff.

From the study of the aquifer hydraulic heads it is estimated that only 0.23 Mm^3 will be guaranteed by aquifer discharge, while the remainder will depend on the hydraulic characteristics of the unsaturated zone and the hydrometeorologic regime. The outflows of the future lake will be evaporation and infiltration.

From the analysis of water resources in La Respina valley it is possible to estimate the time needed to reach the lake maximum water level. In scenario #1, the lake maximum water level will be reached in 9 months, and in scenario #2 the lake maximum water level will be reached in 2.5 years.

The future lake design will impact on the definite landscape of La Respina valley and on the hydrogeology of the surrounding rocks, namely in the flow regime of two springs that are hydraulically connected to the open pit. Since the artificial lake will induce a rise of the hydraulic head in the surrounding rock massif, the impact of the future lake on the flow regime of Springs 1 and 2 will be an increase of their flow.

Acknowledgments

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