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TECHNICAL ARTICLE

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

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Abstract The 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. The open pit is 600 m long by 300 m wide, and has a maximum depth of about 100 m. Karstic springs hydraulically connected to the mine are located down-gradient of the open pit. It is planned that the future lake will be filled using the natural water resources available in the watershed. These water resources have been evaluated by means of a daily-based, lumped hydrologic balance model. The comparison between computed ground water discharges and the flow rates measured at La Respina Springs provide supportive evidence that it is a sound and reliable model. The outputs of the lumped hydrologic balance model have been used as boundary conditions for a finite element hydrogeologic numerical model of the aquifer. By combining the results of both models, a net inflow to the future lake between 2.87 and 3.25 Mm^3/year has been predicted. The future lake will induce the water table to rise and therefore, the base flow of the karstic springs is expected to increase.

Keywords Artificial lake · Hydrogeological modelling · La Respina mine · Water resources assessment

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Introduction

Mining companies must develop closure plans to mitigate social and environmental impacts. Most closure plans for open pit exploitations include the construction of an artificial lake to fill the void space. In many situations, these pit lakes can provide economic, health, welfare, safety or aesthetic benefits to the community (McCullough and Lund 2006, and references therein). Closure plans that foresee the construction of pit lakes need to include estimates of the time that it will take to fill the future lake and the hydrogeologic impacts of its filling.

Different methods to estimate the time to fill pit lakes have been reported, including both analytical and numerical models (Castendyk and Webster-Brown 2007; Davis et al. 2006; Fontaine et al. 2003; Stone and Fontaine 1998; and others). Stone and Fontaine (1998) developed a numerical model in order to simulate the filling of an open pit in Crescent Valley, Nevada that also helped predict pit lake chemistry. In 2003, Fontaine et al. developed an analytical solution, based on the Jacob–Lohman equation, to estimate the time to fill a pit lake, accounting for transient inflow rates, pit geometry, effects of precipitation and evaporation from the lake surface, as well as other external flows.

In the present work, two models—a lumped hydrologic model and a hydrogeologic numerical model—have been coupled to estimate the time to fill the future La Respina open pit lake and its hydrogeologic impacts.

La Respina mine is an open pit, where talc has been mined since 1930; it is located in the NW of Spain, on the southern bank of the Cantabric Chain in the province of Léon. 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 (Fig. 1). The mined formation is a Lower Carboniferous limestone that was subject to dolomitization and subsequent transformation into talc.

The area of the La Respina catchment, from the surface water divide to the location of the La Respina Springs, is 4.7 km^2. The elevation of the La Respina Valley is between 1,500 and 2,000 m above sea level (asl). Its overall hydrogeological behaviour is mainly karstic with some areas behaving as porous media, due to local intensification of fracturing and karstification, and also to blasting of the talc formations.

The open pit is 600 m long by 300 m wide, and has a maximum depth of about 100 m. Three springs (La Respina Springs, Fig. 1) 200 m down-gradient of the open pit are designated (from upstream to downstream) Spring 1, Spring 2, and Spring 3. Springs 1 and 2 are hydraulically connected to the open pit. Since both springs are mainly fed by the partially karstified Carboniferous limestones, their flow regime is essentially karstic; each has a summer flow between 6 and 10 L/s. Spring 3 shows a much higher and seasonally-constant flow rate of about 300 L/s as it is hydraulically isolated from the open pit, and mainly fed by the Ordovician quartzites (Martínez et al. 2006).

The area affected by the talc mining and processing is around 0.783 km^2, with an open pit of 0.192 km^2. The tailings occupy a total area of 0.410 km^2, of which 50% has been reforested.

Under natural conditions, several ephemeral streams flowed into the open pit area (Fig. 1), but these streams were diverted, so that they now discharge to La Respina stream, immediately downstream of the open pit, close to the location of La Respina Springs.

The closure plan of La Respina mine foresees the generation of an artificial lake in the volume left by the open pit. Two alternative designs are being considered: one scenario (#1) has a maximum lake water level 60 m above the open pit bottom (no dam construction needed), while the second scenario (#2) has a maximum lake water level 100 m above the open pit bottom, requiring the construction of a dam (Sena and Molinero 2008).

This assessment of the La Respina mine closure plan is based on: an evaluation of the water resources of the La Respina catchment; an estimation of the time needed to reach the maximum lake water level; and the anticipated hydrogeologic impact of the future lake.

Methods

The evaluation of water resources in La Respina Valley was based on modelling the daily water balance using the program Visual Balan v.1.0 (Samper et al. 1999). This hydrologic model apportions the daily water balance in the soil, unsaturated zone, and the aquifer, which allows the computation of daily ground water levels as well as basin discharge rates. The main inputs of the balance are rainfall, snowfall, and irrigation while the outputs are surface runoff, evapotranspiration, interception, interflow, and ground water flow. The code evaluates all these components in a sequential manner by starting with values for rainfall, snowfall, and irrigation, which must be provided by the user. In addition, the code incorporates two advanced options: automatic parameter estimation using water level and flow rate data, and sensitivity analysis of the main components of the water balance with respect to a wide number of model parameters (for more details, see Samper

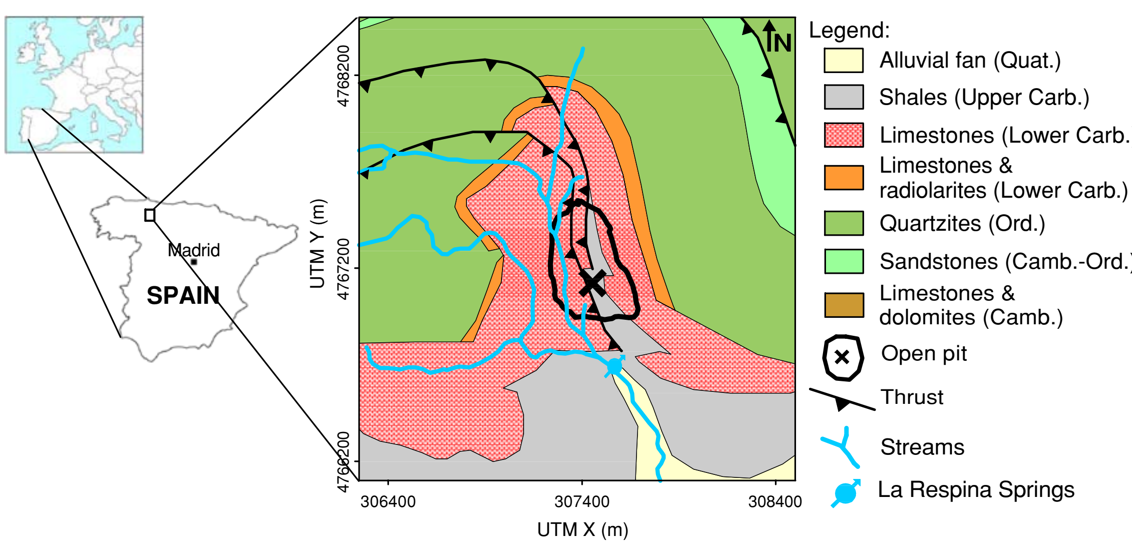

Fig. 1 Location and geology of the study area; digitalised from Lobato et al. 1984

et al. 1999). The hydrologic model that simulates the water balance of La Respina Valley was calibrated by comparing computed hydraulic heads and ground water discharge with a field-collected database.

The outputs of the hydrologic model have been used as boundary conditions in a 2D finite element hydrogeologic numerical model, which in turn was calibrated using the field data used in the previous lumped hydrologic balance model, as well as the flow rate calculated by the latest model for La Respina Springs.

The estimation of the time needed to reach the maximum lake water level is based on the quantification of its volume and the evaluation of water influxes and effluxes of the future lake. Water resources available to fill the future lake have been evaluated in the lumped hydrologic balance model, while the infiltration of the future lake in the surrounding rock massif and its hydrogeologic impact have been evaluated in the 2D finite element hydrogeologic model.

Results and Discussion

Lumped Hydrologic Balance Model

The hydrologic model developed for La Respina Valley is based on the calibration of the hydraulic parameters of the edaphic soil, unsaturated zone, and the aquifer (Table 1). The robustness of this lumped hydrologic balance model has been evaluated by comparing the computed flow rates and hydraulic heads with the observed values.

During 2003 and 2004, the flow rate estimated by the lumped hydrologic balance model for springs 1 and 2 was very close to the observed values, while from 2005 to 2007, the flow rate was overestimated (Fig. 2). The open pit has been drained since 2005, due to continued deepening of the mine bottom, and since the lumped hydrologic balance model does not account for aquifer abstraction, the computed flow rate corresponds to the flow rate that would be observed if no drainage had occurred. In fact, by comparing the flow rate calculated for 2005 with the observed flow rate, the hydrogeologic impact to the springs was estimated at 866 m^3/day. This value is consistent with the amount of water pumped as reported during drainage operations, which proves the robustness of the lumped hydrologic balance model.

The mean annual rainfall at La Respina Valley amounts to 955.6 mm/year (Fig. 3). According to the results of the lumped hydrologic balance model, 57% of precipitation is converted to surface runoff, 19% infiltrates and recharges the aquifer, and 24% is released back into the atmosphere through evapotranspiration (ET). The lateral shallow subsurface flow (also named hypodermic) represents only 0.2% of the annual rainfall. This reflects the steep slopes that characterize the topography of La Respina Valley, which produce considerable runoff, as well as the relatively deep ground water table that favours vertical infiltration.

The future lake is not a component of the hydrologic balance model; therefore, the calculation of its potential evaporation has been done separately. The mean potential evaporation from the lake surface, calculated using the Penman method, is 777.8 mm/year.

From the attained water budget (Fig. 3), the inflows to the future lake are: (1) direct rainfall, (2) direct snow melt, (3) runoff, (4) lateral flow, and (5) aquifer discharge. The outflows from the future lake are evaporation and infiltration. All the lake inflows are outputs of the lumped hydrologic balance model, and therefore their estimation

Table 1 Calibrated values for the hydraulic parameters of the main components of the lumped hydrologic balance model, obtained through in situ observation and analysis of site specific characteristics and professional judgement

Component of the hydrologic cycle	Parameter	Calibrated value
Edaphic soil	Field capacity (volume %)	35
	Wilting point (volume %)	10
	Hydraulic conductivity (m/s)	1.16×10^{-6}
Unsaturated zone	Depletion coefficient for lateral flow (day^{-1})	0.01
	Vertical hydraulic conductivity (m/s)	1.16×10^{-4}
	Depletion coefficient for percolation (day^{-1})	1
Aquifer	Depletion constant (day^{-1})	8.50×10^{-3}
	Storage coefficient (dimensionless)	6.00×10^{-3}

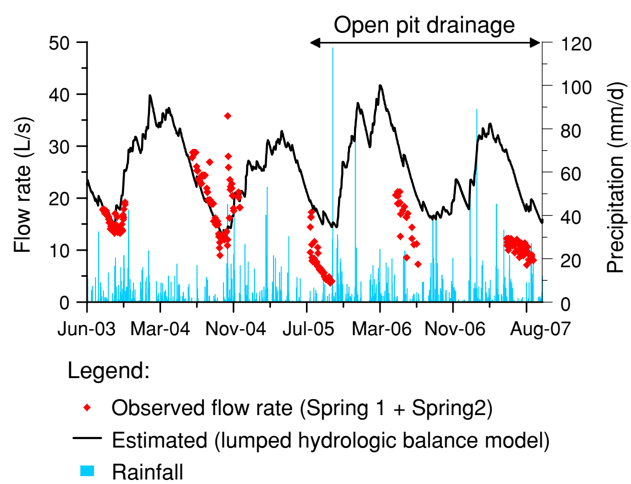

Fig. 2 A comparison of the estimated flow rate for the sum of springs 1 and 2 and the observed values; model calibration was developed only for the period before the open pit drainage

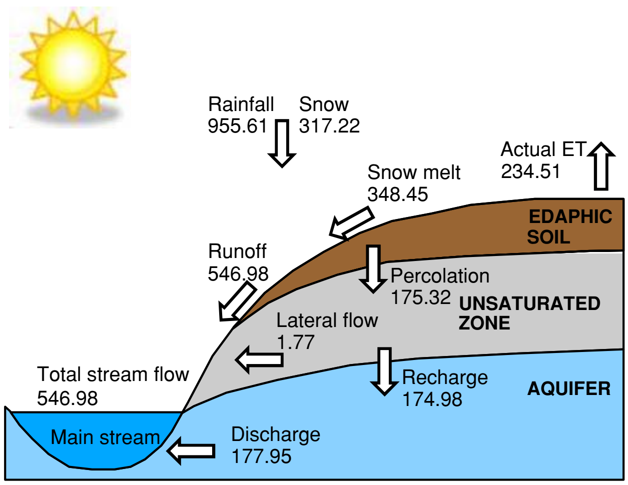

Fig. 3 Mean annual water balance (in mm/year) of La Respina Valley calculated using Visual Balan v.2.0 (Samper et al. 1999)

depends on its calibration, which is subject to some degree of uncertainty, but, as previously demonstrated, it is a robust model.

Hydrogeologic Model

In order to estimate the hydrogeologic impact of the future lake, a finite element hydrogeologic numerical model was built using the code Feflow (Diersch 2005). The model simulates a 2D vertical section of La Respina Valley along a possible ground water flow line, from the surface water divide to La Respina Springs.

A steady state model was built to evaluate the natural configuration of the water table represented by the 2D hydrogeologic model, with the following boundary conditions: the mean specific recharge to the aquifer, as calculated by the lumped hydrologic balance model (174.98 mm/year, in Fig. 3) has been prescribed on the top boundary of this model, representing the topography of La Respina Valley, and a constant hydraulic head, corresponding to the natural elevation of the topographic surface (which is 1,490 m asl, Fig. 4), has been prescribed at the location of La Respina Springs.

The spatial discretization of the modelled domain has been set according to the geometric elements that influence ground water flow directions, namely the open pit where the future lake will be filled, and La Respina Springs (Fig. 4). The future lake is expected to generate a radius of influence due to the infiltration of the lake water which, in turn, triggers important vertical and downward water flow lines. In addition, all the water that enters the modelled domain will leave through La Respina Springs, which generates an area of confluence of ground water flow lines.

The flow rate calculated by the steady state model for La Respina Springs is 30 L/s, which is approximately the average flow rate estimated by the previous lumped hydrologic balance model (Fig. 2). The estimated hydraulic heads also agree with the observed values, which corroborates the reproducibility of the hydrogeologic model (observation points shown in Fig. 5).

The 2D hydrogeologic model has been calibrated by prescribing the daily recharge to the aquifer (calculated by the previous lumped hydrologic balance model), and comparing the resulting flow rate estimated for La Respina Springs with the field-measured values and the flow rate (previously computed by the lumped hydrologic balance model). The evolution of the computed hydraulic heads has also been compared with the hydraulic heads measured at the observation points that are identified in Fig. 5.

Results from the hydrogeologic model show good agreement with both estimated (by the lumped hydrologic balance model) and observed flow rates and hydraulic heads

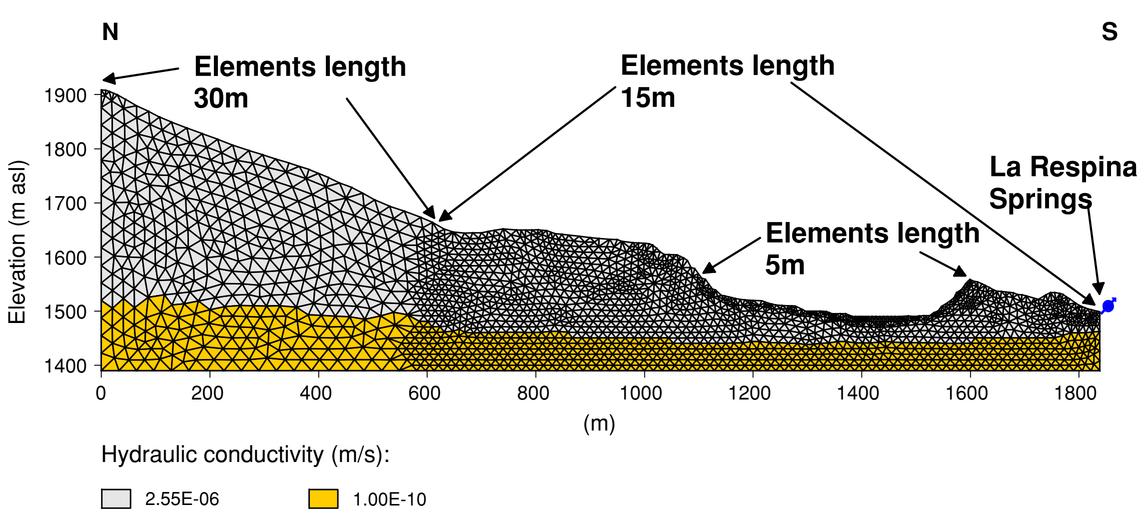

Fig. 4 Spatial discretization of the modelled domain and distribution of the hydraulic conductivity

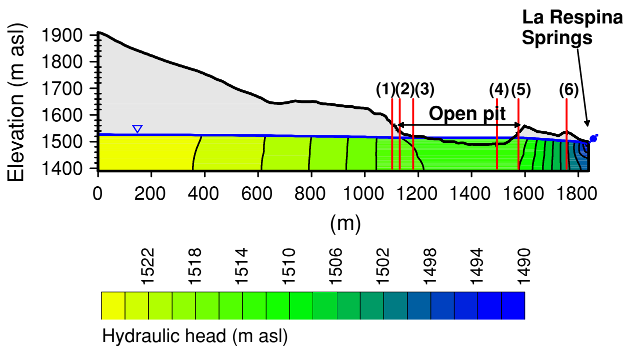

Fig. 5 2D hydrogeologic model showing water table and hydraulic heads that result from a steady state with a constant recharge of 174.98 mm/year. Numbers *1–6* indicate the location of observation points used for model calibration

(only flow rates are shown in this paper, Fig. 6). The flow rate estimated by the lumped hydrologic balance model is approximately the moving average of the hydrogeologic finite elements model, and the latter is able to reproduce the peak flow rates observed in the springs (Fig. 6). These results reflect the different features of both models.

The hydraulic conductivity of the 2D hydrogeologic model is considered stratified, being higher above the elevation of La Respina Springs, and four orders of magnitude lower, below this elevation. The stratification of the hydraulic conductivity represents the higher degree of fracturing/karstification in the upper part of the domain, due to the dissolution of the carbonate bedrock. The hydraulic conductivity calibrated for the upper part of the domain is 2.55×10^{-6} m/s. This value represents the equivalent hydraulic conductivity of the bedrock that is up-gradient of La Respina Springs, and is influenced by the karstic system.

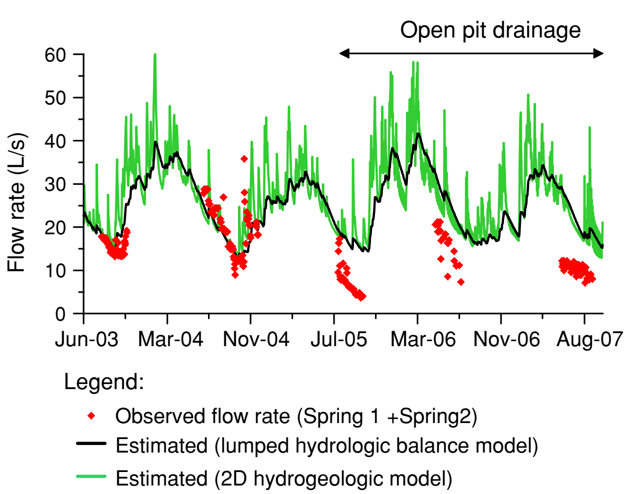

Fig. 6 A comparison of the flow rate of springs 1 and 2, as estimated by the hydrologic and 2D hydrogeologic models, and the observed values. Model calibration was developed only for the period before the open pit drainage

Field data from pumping tests (two bailing tests and one step-drawdown test) reveal that in the karstic areas, the bedrock has a local average hydraulic conductivity of 1.715×10^{-4} m/s, while in relatively fresh rock (i.e. non-weathered rock) areas, the hydraulic conductivity has an average value of 5.5×10^{-9} m/s (unpublished pumping test analysis). The equivalent hydraulic conductivity is within the range of the field values.

If the direction of the regional ground water flow is considered parallel to the karst conduits, which is a reasonable approximation, it is possible to estimate the fraction of karst in the aquifer, using the following equation:

$$k_{eq} = \frac{\sum_{i=1}^{n} k_i b_i}{\sum_{i=1}^{n} b_i} \quad (1)$$

where, k_{eq} is the equivalent hydraulic conductivity; k_i is the hydraulic conductivity of layer i of the aquifer; b_i is the thickness of layer I; and n is the number of layers that compose the aquifer.

A karst fraction of 1.45% has been estimated for the studied aquifer by using Eq. 1 to relate the calibrated equivalent hydraulic conductivity (2.55×10^{-6} m/s) with the hydraulic conductivities obtained in field tests for the karstified (1.715×10^{-4} m/s) and fresh rock (5.5×10^{-9} m/s). This value is relatively low, meaning that the karst system of the modelled aquifer is not well developed. In addition, the evolution of the spring discharges, with marked seasonality and steep peaks related to rainy events (Fig. 6), reflects the relatively low hydraulic conductivity and storage coefficient of the aquifer.

The hydrogeologic impact of the future lake has been evaluated in the 2D hydrogeologic model by prescribing a constant hydraulic head in the open pit extension (Fig. 5) that represents the maximum lake water level in each scenario. In scenario #1, an increase of the base flow of La Respina Springs of approximately 1.2 times their natural base flow is expected, while in scenario #2, an increment of approximately 1.6 times the natural base flow of La Respina Springs is predicted (Fig. 7).

The expected increase of the flow rate of La Respina Springs will be due to infiltration of future lake water, which is expected to decrease with time due to the deposition of fine grained sediments at the bottom of the future lake. The maximum infiltration rate has been calculated from the difference between the flow rate expected for La Respina Springs in each scenario under study and their natural flow rate. The calculated maximum infiltration rate is 5.73 L/s in scenario #1 and 17.2 L/s in scenario #2.

Assessment of the Future Lake

The possible dimensions of the future lake have been assessed for both scenarios. In scenario #1, the volume of

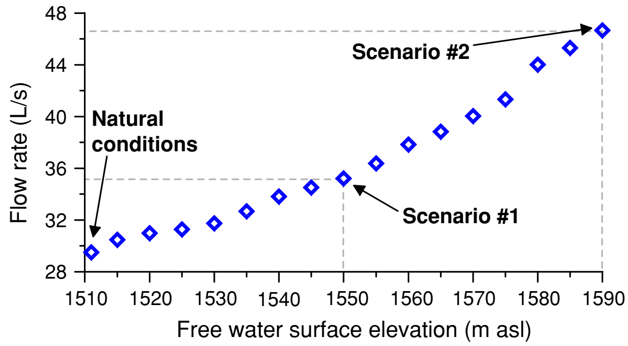

Fig. 7 Flow rate estimated for La Respina Springs for different elevations of the free water surface of the future lake. The natural mean flow rate of La Respina Springs is ≈30 L/s. In scenario #1, the flow rate is estimated to be ≈35 L/s, while in scenario #2, it is estimated to be ≈47 L/s

the future lake is expected to be 1.94 Mm^3, with a free water surface of 0.07 km^2, while in scenario #2, a volume of 5.75 Mm^3 is expected, with a free water surface of 0.12 km^2. The maximum lake water column is expected to be 60 m in scenario #1, and 100 m in scenario #2. Scenario #2 will cover a larger area of the open pit, which may lead to a better landscape design, but requires the construction of a dam in the lower part of the open pit border (Fig. 8), which increases the costs and complexity of the closure plan.

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 steepens towards 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 1,511 m asl, which means that the lowest 0.23 Mm^3 of the future lake will be guaranteed by aquifer discharge, whilst the remainder will be fed by surface and subsurface water fluxes. Based on the Fig. 5 cross section, the simulated hydraulic gradient ranges from 0.013 in the north to 0.08 in the south, which agrees reasonably well with the natural hydraulic gradient of the area.

By combining the outputs of the lumped hydrologic balance model and the hydrogeologic model, it is possible to estimate the mean annual net inflow to the future lake. The calculations performed for the mean net inflow to the future lake and the estimation of the corresponding time to fill the future lake are summarised in Table 2.

The mean net inflow computed from the available water resources is 3.25 Mm^3/year for scenario #1, and 2.87 Mm^3/year for scenario #2. In scenario #1, the lake volume above the water table is 1.71 Mm^3, meaning that the maximum lake level will be reached in approximately 6 months. In scenario #2, the lake volume above the water table is 5.52 Mm^3, meaning that the maximum lake water level will be reached in approximately 1.9 years.

Conclusions

The natural water resources of La Respina Valley will contribute to the filling of the future lake, with the main inflow being surface runoff. From the study of the aquifer hydraulic heads, it is estimated that 0.23 Mm^3 will be guaranteed by aquifer discharge, while the remainder will be fed by the natural subsurface and surface water resources. These water resources depend on the hydrometeorologic

Fig. 8 Aerial orthophotograph of La Respina mine, showing the limits of the open pit and future lake, and a cross section view of the open pit, showing the elevation of the minimum hydraulic head and the maximum water level of the future lake

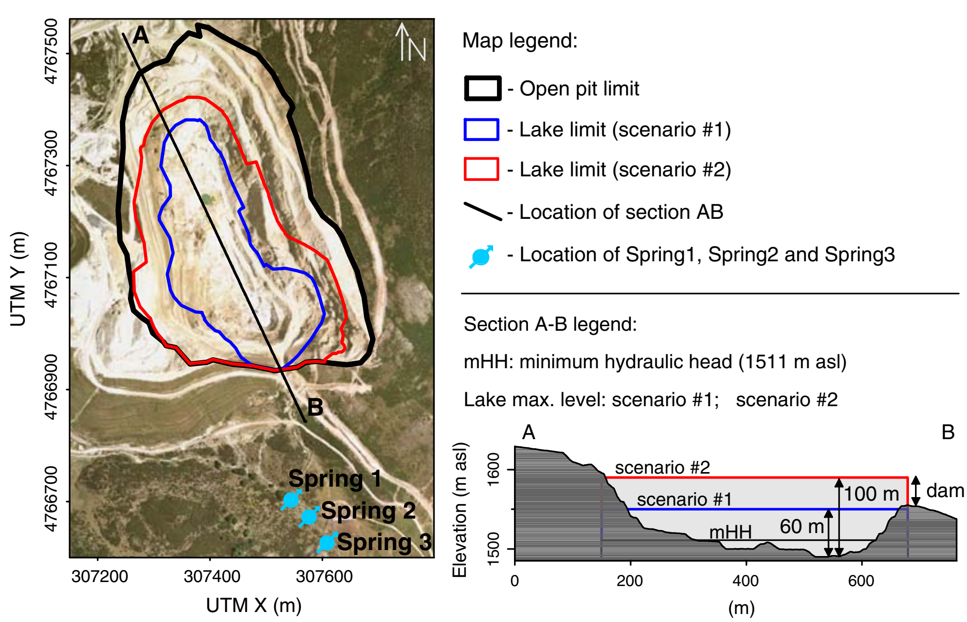

Table 2 Summary of the calculations performed for the mean net inflow to the future lake and the corresponding time to fill the future lake

Watershed area (m^2)	3,915,205	
Scenario	1	2
Lake surface area (m^2)	66,170	123,650
Watershed area minus lake surface area (m^2)	3,784,464	3,726,984
1 Direct rainfall on lake surface (m^3/year)[a]	6.323×10^4	1.182×10^5
2 Evaporation from lake surface (m^3/year)[b]	5.147×10^4	9.618×10^4
3 Infiltration from lake bottom (m^3/year)[c]	1.806×10^5	5.414×10^5
4 Direct snow melt on lake surface (m^3/year)[a]	2.306×10^4	4.309×10^4
5 Snow melt on watershed (m^3/year)[d]	1.319×10^6	1.299×10^6
6 Surface runoff on watershed (m^3/year)[d]	2.070×10^6	2.039×10^6
7 Lateral flow from watershed (m^3/year)[d]	6.699×10^3	6.597×10^3
8 Mean net inflow (m^3/year) (**1** – **2** – **3** + **4** + **5** + **6** + **7**)	3.250×10^6	2.868×10^6
9 Lake volume above the water table (m^3)	1,709,140	5,516,440
Mean time to fill the future lake (years) (**9/8**)	0.5	1.9

[a] Value obtained by multiplying the corresponding specific flow rates computed in the lumped hydrologic model (shown in Fig. 3) by the lake surface area

[b] Value obtained by multiplying the potential evaporation of 777.8 mm/year (calculated using the Penman method) by the lake surface area

[c] Value obtained from the outputs of the hydrogeologic numerical model

[d] Value obtained by multiplying the corresponding specific flow rates computed in the lumped hydrologic model (shown in Fig. 3) by the watershed area minus the lake area

regime of La Respina Valley, as well as on the hydraulic characteristics of the unsaturated and saturated zones. The outflows of the future lake will be evaporation and infiltration. The lake will be a flow through pit for ground water, but not surface water.

The inflows of the future lake have been evaluated in a lumped hydrologic balance model that was calibrated against measured hydraulic heads and spring discharges, while evaporation from the free water surface of the future lake has been estimated using the Penman method. Under the hydrometeorologic conditions that prevail nowadays, it appears that evaporation from the future lake will be very small compared to the inflows available for the future lake.

By combining the results attained in the lumped hydrologic balance model and the 2D hydrogeologic model, it has been estimated that the maximum lake water level will be reached in approximately 6 months in scenario #1, and in approximately 1.9 years in scenario #2.

The future lake design will have a major impact on the landscape of La Respina Valley and the flow regime of the two springs that are hydraulically connected to the open pit. Since the artificial lake will increase the hydraulic head in the surrounding rock massif, the flows from these springs will increase by $\approx$1.2 times their natural base flow in scenario #1, and $\approx$1.6 times their natural base flow in scenario #2.

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