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Hydrochemical changes induced by underground pumped storage hydropower: influence of aquifer parameters in coal mine environments

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Abstract. Underground pumped storage hydropower (UPSH) induces hydrochemical changes when water evolves to reach equilibrium with the atmosphere (in the surface reservoir) and with the surrounding medium (in the underground reservoir). These hydrochemical changes may impact the environment and the efficiency of the system (i.e., the UPSH plant), especially in coal mine environments where the presence of sulphide minerals is common. For this reason, it is needed to assess the variables that control the behavior of the system in order to establish criteria for the selection of abandoned mines to be used as underground reservoirs in future UPSH plants.

Coupled hydro-chemical numerical models are used for investigating the influence of hydraulic parameters on the hydrochemical changes when pyrite is present in the surrounding medium. Results show the role of the hydraulic conductivity and the porosity on the system behavior, which is helpful for selecting those abandoned mines where the hydrochemical changes and their associated consequences will be less.

1 Introduction

Underground pumped storage hydropower (UPSH) is an alternative energy storage system (ESS) for flat regions (Pujades et al., 2016; Pummer and Schüttrumpf, 2018). UPSH plants consist in two reservoirs, one is underground while the other is located at the surface (Barnes and Levine, 2011). The excess of electricity generated during low demand energy periods is used for pumping water from the underground to the surface reservoir, and when the demand of energy increases, water is released into the underground reservoir through turbines for generating electricity. Although there are not bibliographical evidences of UPSH constructed plants, this technology has been investigated in different parts of the world: the Netherlands (Min, 1984), Singapore (Wong, 1996), USA (Allen et al., 1984; Severson, 2011), Germany (Beck and Schmidt, 2011; Zillman and Perau, 2015; Alvarado et al., 2016), Belgium (Bodeux et al., 2016; Poulain et al., 2018), Spain (Menéndez et al., 2017) and South Africa (Winde and Stoch, 2010a, b; Khan and Davidson, 2016; Winde et al., 2017), Finland and Australia (Academy of Science of South Africa, 2016).

Although it would be possible to drill the underground reservoir, the alternative considered in this paper, which may be more efficient and have positive effects for local communities after the cessation of mine activities, would consist in re-using abandoned mines. The main concern of UPSH using abandoned mines is the water exchanges between the underground reservoir and the surrounding porous medium because they can affect the environment and the efficiency of the UPSH plant. Most studies focused on water exchanges consider flow related issues (Bodeux et al., 2017; Pujades et al., 2017a). However, recently, Pujades et al. (2017b) have suggested the importance of considering hydrochemical changes induced by UPSH plants. These changes may impact on the environment and affect the efficiency of the plant.

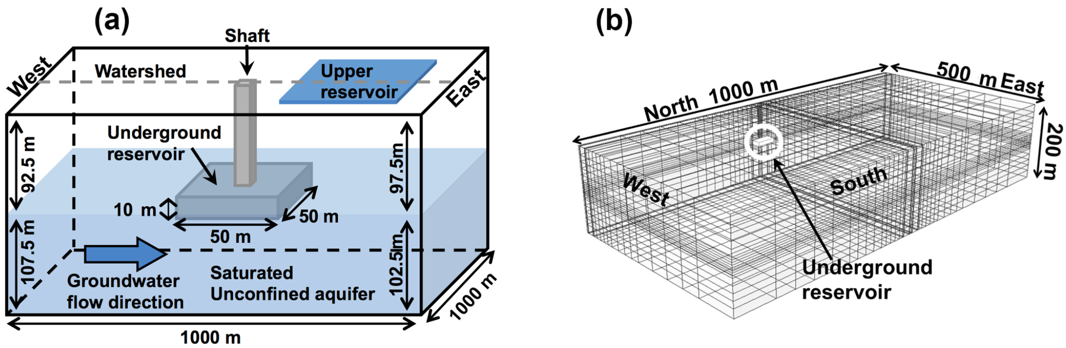

Figure 1. General view of the problem **(a)** and the whole modelled domain **(b)**.

Water is aerated when it is pumped, discharged and stored in the surface reservoir. As a result, its chemistry evolves to reach equilibrium with the atmosphere. Similarly, when water is discharged into the underground reservoir, its chemistry evolves to reach equilibrium with the surrounding porous medium. These hydrochemical changes may produce pH variations, especially in coal mine contexts where pyrite is a common mineral. Its oxidation leads to pH lowering. Low pH values would affect the environment (decreasing the quality of groundwater and surface water bodies) and the efficiency of the plant (corroding UPSH facilities such as pipes, turbines, pumps or concrete structures).

Although the general behaviour of the system has been previously stated (Pujades et al., 2018), there is not any study in which the influence of the aquifer hydraulic parameters on a UPSH system is assessed. To establish the role of aquifer hydraulic parameters will be meaningful for selecting the most suitable places where constructing future UPSH plants. Thus, the main objective of this work is to investigate the importance of the hydraulic parameters on the pH variations occurring when abandoned coal mines (with presence of pyrite) are used for UPSH.

2 Methods

2.1 Problem statement

A 200 m thick domain with an underground reservoir in the middle is considered (Fig. 1a). The reservoir (50×50 m and 10 m of height) is saturated in natural conditions with the top and bottom located respectively at 95 and 105 m depth. The water table is located at 92.5 and 97.5 m depth in the upgradient and downgradient boundaries, respectively. Thus, the underground reservoir is located at the top of an unconfined porous medium whose saturated thickness ranges between 107.5 and 102.5 m. The outer boundaries are located at 500 m from the underground reservoir. The hydraulic gradient under natural conditions is 0.005.

Frequency of pumping and discharging phases is chosen according to day/night cycles (i.e., 12 h pumping and 12 h discharging water). Pumping and discharging rates are 43 000 $m^3\,d^{-1}$. These rates allow decreasing and increasing the hydraulic head inside the underground reservoir up to 8.6 m during each pumping-discharging cycle.

It is assumed that the modelled cavity belongs to an abandoned coal mine. Coal deposits usually contain sulphide minerals, whose oxidation may entail important consequences for water chemistry. Pyrite is the most common sulphide mineral in this kind of deposits (Akcil and Koldas, 2006), and thus, it is assumed that the porous medium contains 1 % pyrite. Reaction rates for the other minerals (e.g. silicates) are assumed very low (White and Brantley, 1995), and are neglected.

2.2 Numerical model

The code PHAST (Parkhurst et al., 1995; Parkhurst and Kipp, 2002) is used to simulate the problem. This code solves multicomponent, reactive solute transport in three-dimensional saturated groundwater flow (Parkhurst et al., 2010). The watershed divide crossing the domain from the west to the east boundaries (Fig. 1a) allows modeling only half of the domain without affecting the results. The modeled "half-domain" is divided in 15 600 elements whose size ranges from 2 to 100 m (they are refined towards the underground reservoir) (Fig. 1). Dirichlet boundary conditions (BCs) are implemented in the west and east boundaries with head prescribed at 92.5 and 97.5 m depth, respectively. Flow-rate BCs are adopted in nodes located inside the underground reservoir for simulating the pumpings and discharges. The values of longitudinal (α_L) and transversal (α_T) dispersivity are 10 and 1 m, respectively. The underground reservoir is modelled by implementing a high value of K (10^6 m d^{-1}), S of 1, and a dispersivity of 10^4 m in the three directions. The validity of the assumptions adopted for modelling the underground reservoir has been evaluated by Pujades et al. (2017b). Three different scenarios (Sce1, Sce2 and Sce3) are simulated and compared to ascertain the influence of the hydraulic conductivity (K) and porosity (Φ) values in the surrounding porous medium on the system behaviour. K and Φ are 0.01 m d^{-1} and 0.05, respectively, in

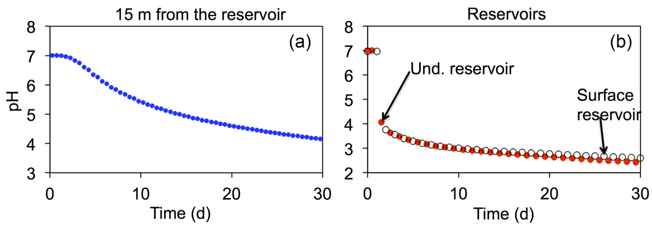

Figure 2. pH evolution in the surrounding porous medium at 15 m from the underground reservoir **(a)**. pH evolution in the reservoirs **(b)**. These results are obtained for Sce1.

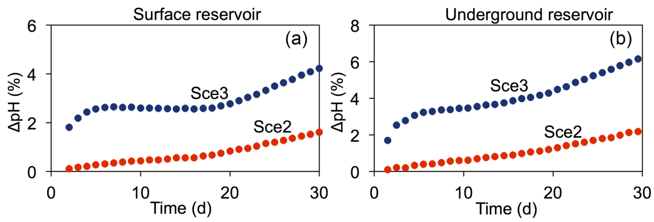

Figure 3. pH differences in the surface **(a)** and underground reservoirs **(b)**.

Sce1. K is increased in Sce2 up to 0.1 m d^{-1}, while Φ is increased in Sce3 to 0.25. The hydraulic parameters (K and Φ) remain constant during the simulated period. This particularity does not affect noticeably the results because the variation of Φ is negligible (Pujades et al., 2018).

2.3 Basic concepts

Pujades et al. (2018) stated the main trends of the system. Dissolved oxygen increases when the water is pumped, discharged and stored in the surface reservoir. When this water is discharged in the underground reservoir and is exchanged with the surrounding porous medium, it oxidizes pyrite decreasing the groundwater pH (Fig. 2). Pyrite is oxidized until all available oxygen is consumed. Subsequently, water is pumped, discharged and stored in the surface reservoir and the dissolved oxygen increases again. pH in the underground reservoir decreases when it is filled with groundwater from the surrounding porous medium (Fig. 2). As a result, when this water is pumped to the surface reservoir, pH also decreases on it. In addition, minerals such as ferrihydrite, goethite and schwermannite may precipitate in the surface reservoir contributing also to the pH reduction.

3 Results

Results show the differences in percentage between Sce1 and the scenarios Sce2 and Sce3. A positive difference means that computed results (for Sce2 and Sce3) are higher than those obtained for Sce1 while differences are negative when they are lower.

3.1 Underground and surface reservoirs

Figure 3 shows the results concerning the pH evolution in the surface (left) and underground reservoirs (right). pH is higher for both scenarios (Sce2 and Sce3) than that computed for Sce1. pH decreases less for Sce2 and Sce3 than for Sce1 because the volume of groundwater reaching the reservoir from the upgradient side, which is less affected by the pyrite oxidation, increases when the values of K and Φ are incremented. In principle, pH difference should increase constantly with time as the volume of water reaching the underground reservoir from the upgradient side. However, after an initial increase, the pH difference remains nearly constant, especially between Sce3 and Sce1, and the pH difference with respect Sce1 only start to increase constantly after 20 simulated days. This behaviour may be related with the precipitation of schwertmannite in the surface reservoir, which releases H^+ (i.e., reduces the pH). In addition, the precipitation rate of schwertmannite decreases with pH and stops for pH values lower than 2.8. Therefore, given that pH in Sce2 and Sce3 are higher than in Sce1, more schwertmannite precipitates, which contribute to decrease the pH and avoid a constant increase of the pH difference between scenarios. However, after 20 days, the precipitation of schwertmannite stops and pH difference between scenarios only depend on the groundwater reaching the reservoir from the upgradient side. As a result, the pH difference starts to increase constantly.

3.2 Surrounding medium

Figure 4 shows the results concerning the pH evolution in the surrounding porous medium. pH is computed at a distance of 15 m from the underground reservoir (in the downgradient side). In Sce2, pH is lower than that for Sce1 because dissolved oxygen reaches faster the surrounding medium (dissolving more pyrite) and groundwater with low pH flows faster until the distance at which the pH is computed. Contrarily, pH decreases less for Sce3 than in Sce1 although the water exchanges increase and the dissolved oxygen reaches faster the surrounding medium. In this case (Sce3), the volume of water in the aquifer is higher than that of Sce1 and the pH reduction is buffered (i.e., there is a dilution effect).

4 Conclusions

This work investigates the influence of the hydraulic conductivity and the porosity on the hydrochemical changes induced by UPSH. Results could be helpful for defining screening strategies, which should be used for the selection of potential abandoned coal mines to construct future UPSH plants.

Results show that pH decreases less in the reservoirs but more in the surrounding porous medium when the value of K

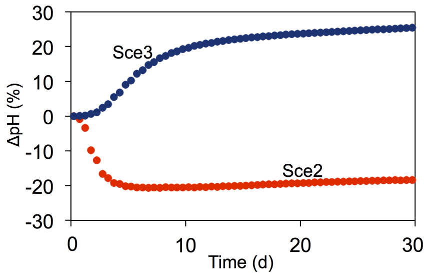

Figure 4. pH differences in the surrounding porous medium. pH is computed 15 m far away from the underground reservoir in the downstream direction.

is raised. This behaviour in the reservoirs is positive for mitigating corrosion problems in the plant facilities (e.g., pipes, turbines, pumps) and the environmental impact if some water from the surface reservoir is accidentally discharged in surface water bodies. However, the mitigation of the corrosion and environmental impact in surface water bodies would be very limited since pH difference between Sce2 and Sce1 in the reservoirs are lower than 5 %. Contrary, the pH decreases approximately the 20 % in comparison with Sce1 in the surrounding porous medium, which would increase the environmental impact on groundwater. Given these results, coal mines surrounded by materials with low values of K would be preferable for mitigating the environmental impact.

A different behaviour is observed when porosity is increased. In this case, pH decreases less in the reservoirs and also in the surrounding porous medium. In that particular case, the adverse effects of UPSH in the presence of pyrite would be mitigated. Thus, coal mines surrounded by materials with high values of porosity would be preferable for constructing UPSH plants.

Data availability. Data containing the numerical results presented in this article are openly available in Open Science Framework at http://doi.org/10.17605/OSF.IO/BCN7K (Pujades, 2018).

Competing interests. The authors declare that they have no conflict of interest.

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