



European Geosciences Union General Assembly 2017, EGU  
Division Energy, Resources & Environment, ERE

## Water chemical evolution in Underground Pumped Storage Hydropower plants and induced consequences

Estanislao Pujades<sup>a,\*</sup>, Philippe Orban<sup>a</sup>, Anna Jurado<sup>a</sup>, Carlos Ayora<sup>b</sup>, Serge Brouyère<sup>a</sup>,  
Alain Dassargues<sup>a</sup>

<sup>a</sup>Hydrogeology and Environmental Geology, Geo3, Dpt ArGenCo, Aquapole, University of Liege, 4000 Liege, Belgium

<sup>b</sup>GHS, Institute of Environmental Assessment & Water Research (IDAEA), CSIC, Jordi Girona 18-26, 08034 Barcelona, Spain

---

### Abstract

Underground Pumped Storage Hydropower (UPSH) is an alternative to manage the electricity production in flat regions. UPSH plants consist of two reservoirs of which at least one is underground. For this last reservoir, abandoned mines could be considered. UPSH related activities may induce hydrochemical variations, such as the increase of the oxygen (O<sub>2</sub>) partial pressure (pO<sub>2</sub>), which may entail negative consequences in terms of environment and efficiency, especially in coal mined areas where the presence of sulfide minerals is common. This work assesses the main expected environmental impacts that UPSH using abandoned coal mines may induce.

© 2017 The Authors. Published by Elsevier Ltd.

Peer-review under responsibility of the scientific committee of the European Geosciences Union (EGU) General Assembly 2017 – Division Energy, Resources and the Environment (ERE).

*Keywords:* Groundwater; Coal mine; Pumped Storage Hydropower; Reactive transport

---

### 1. Introduction

One of the main concerns with respect to solar and wind energies, is that the electricity production is highly variable and is hardly adapted to the demand [1-5]. This fact tends to reduce their efficiency and limits their applicability. Energy storage systems (ESSs) are needed to manage the electricity production from renewable

---

sources and increase their utilization [6]. Underground Pumped Storage Hydropower (UPSH) [7] is an ESS that allows a large amount of electricity to be stored and produced. UPSH plants consist of two reservoirs, the lower one is underground while the upper one is located at the surface or at shallower depth [8]. The main advantage of UPSH is that it is not limited by the topography. Thus, UPSH is a potential alternative to manage the electricity production in flat regions, where conventional Pumped Storage Hydropower plants cannot be installed.

The underground reservoir for UPSH plants can be excavated, but possibly the cheapest option, which is that considered in this work, consists in using abandoned underground cavities such as deep mines. The main concern regarding the use of abandoned mines is that their walls are not generally impervious, and thus pumped and stored water will interact with the surrounding porous medium. In previous studies, this interaction only has been considered from a water flow point of view determining the impacts produced by the water exchanges (1) on the natural piezometric head of the surrounding porous medium [9,10], and (2) on the efficiency of the plant [11,12]. Here, we focus on hydrochemistry modifications induced by UPSH related activities and predicted associated impacts on the environment.

In a hypothetical UPSH plant using an abandoned mine, pumped water to the surface (i.e., upper) reservoir is aerated and its initial chemical composition evolves to be in equilibrium with the atmosphere leading to an increase of  $pO_2$  and associated chemical reactions. In addition, when this water is released into the underground reservoir, this may react with the surrounding porous and fractured medium and with the water occupying the reservoir. It may induce the precipitation or dissolution of minerals and its associated impacts (e.g., reduction or increase of the pH). In the specific case of abandoned coal mines, where sulfides are frequent [13], the increase of  $pO_2$  in the upper reservoir may induce sulfide oxidation when the water is released in the underground reservoir. This fact would lead to very low pH values [14] (i.e., acidification) and then affect the surrounding groundwater quality through the seepage exchange fluxes between the underground reservoir and the surrounding geological layers.

It is thus of paramount importance to assess the environmental impacts and hydrochemical variations induced by UPSH when abandoned coal mines are used. This assessment must be done with regards to the Water Framework Directive [15] adopted by the European Union in October 2000, requiring that nations must guarantee the “good state” of the “water bodies”. Here, those groundwater quality impacts are investigated through a numerical reactive transport model. The main objective of this study is to establish potential impacts on the environment and highlight the importance of considering them for the design of future UPSH plants.

## 2. Materials and methods

### 2.1. Problem statement

The problem is sketched schematically in Fig. 1. The underground reservoir consists in a cavity of 50 by 50 m on 10 m height. The top and bottom of the underground reservoir are at 95 and 105 m depth, respectively. The underground reservoir is linked to the surface through a shaft of 10 by 10 m on 95 m height. The surrounding porous medium is 200 m thick and the external boundaries of the model are located at a 1000 m distance far from the underground reservoir. Under natural conditions, groundwater flows along the domain from the west to the east boundary since the head is chosen at 90 and 110 m depth on the west and east boundaries, respectively. The unconfined aquifer has a saturated thickness ranging between 110 and 90 m. In the central part of the domain, where the underground reservoir is located, the initial natural water level is corresponding to the top of the reservoir (95 m depth). Thus, it is totally saturated at the beginning.

Representative results are obtained assuming day/night cycles of 12 hours (i.e., water is pumped during 12 hours and released during the next 12 hours). Pumping/injection rates are  $43000 \text{ m}^3/\text{d}$ . Thus, the underground reservoir is almost emptied and filled during each pumping/injection cycle (only 1.4 m remains saturated after pumping).

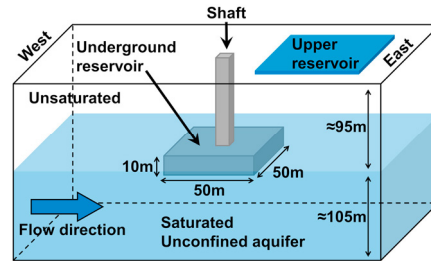


Fig. 1. View of the considered simplified problem.

## 2.2. Numerical model

The problem is simulated using the code PHAST [16,17]. PHAST solves multicomponent, reactive solute transport in three-dimensional saturated groundwater flow [18]. Geochemical reactions are solved by the geochemical code PHREEQC [19,20] while flow and transport are solved with a modified version of HST3D [21,22]. Taking advantage of the problem symmetry (i.e., there is a no-flow boundary just in the center crossing the domain from the west to the east boundaries), only the half of the problem is modeled (Fig. 2).

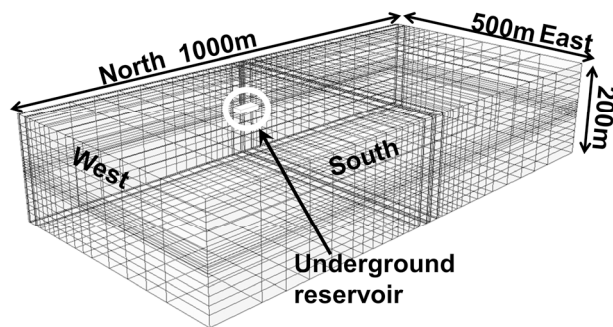


Fig. 2. View of the meshed numerical model with half of the considered problem.

It is assumed that the hydraulic conductivity ( $K$ ) and storage coefficient ( $S$ ) (i.e., effective drainage porosity in unconfined conditions) of the surrounding porous medium are respectively 0.01 m/d and 0.05. Dispersivity is assumed to be 10 m in the flow direction (west to east direction) and 1 m in the other two orthogonal directions. The underground reservoir is simulated by adopting a very large value for  $K$  of  $10^5$  m/d and  $S$  of 1. A very high dispersivity (in the three main directions) is adopted for the underground reservoir:  $10^4$  m. It means that released water is mixing rapidly and homogeneously with the water filling the reservoir. A sensitivity analysis of the adopted dispersivity for the underground reservoir is performed by comparing the results of different scenarios in which dispersivity is reduced up to 10 m. Dirichlet boundary conditions (BCs) are adopted in the west and east boundaries to allow groundwater flow through those boundaries. An initial hydraulic gradient of  $5 \cdot 10^{-3}$  is obtained by prescribing the piezometric head at a depth of 90 m and 100 m on the west and east boundaries, respectively. Pumping and injection are simulated by prescribing flow-rate BCs in nodes located inside the underground reservoir. In total, pumping and injection rates (distributed on the nodes located inside the reservoir) are  $21500 \text{ m}^3/\text{d}$ . Note that this value is half that specified in section 2.1 because only half of the problem is modeled.

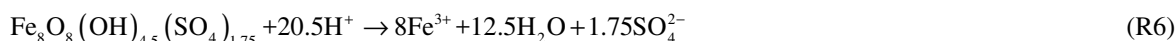
### 2.3. Hydrochemistry

Pyrite is usually the most common sulfide mineral in coal mined environments [23]. Thus, it is considered that the surrounding porous medium contains 0.25% of pyrite. This value can be considered as a conservative high value. It is assumed that the rest of the porous medium is not reacting or reacting with very slow rates. Groundwater that (1) initially is placed in the domain (i.e., underground reservoir and porous medium), (2) enters through the west boundary during all simulated time and (3) flows out through the east boundary at the beginning are in equilibrium with pyrite of the matrix (0.25%). The chemical composition of the injected water during each cycle is defined from the characteristics of the pumped water (of the previous cycle) and considering that water in the upper reservoir reaches equilibrium with atmospheric O<sub>2</sub>. Thus, assuming that pO<sub>2</sub> reaches a value of 10<sup>-0.7</sup> before injection into the underground reservoir.

Main reactions occurring in the system are as follows:



Ferrihydrite ( $\approx\text{Fe}(\text{OH})_3$ ) precipitation induced by reaction R3 may occur if the water pH is higher than 6. Other minerals precipitate with lower values of pH. Goethite ( $\text{FeOOH} + 3\text{H}^+$ ) may precipitate for pH between 4 and 6, whilst schwertmannite ( $\text{Fe}_8\text{O}_8(\text{OH})_{4.5}(\text{SO}_4)_{1.75}$ ) precipitates for pH lower than 4 [24]. Goethite and schwertmannite precipitate as follows:



High pO<sub>2</sub> induces pyrite oxidation (R1) and dissolution in Fe<sup>2+</sup>, SO<sub>4</sub><sup>2-</sup> and H<sup>+</sup>. Thus, pyrite oxidation produces a decrease in pH. If O<sub>2</sub> is still available after R1, R2 may occur and Fe<sup>2+</sup> is transformed in Fe<sup>3+</sup>, which consumes protons. The amount of protons consumed by R2 are much less than those produced by R1. Therefore, R2 cannot counterbalance the pH reduction induced by R1. After that, ferrihydrite (R3), goethite (R5) or schwertmannite (R6) precipitate depending on the pH of the solution. The common characteristic of these three reactions is that they contribute to the pH reduction. Finally, available Fe<sup>3+</sup> reacts oxidizing more pyrite (R4). These reactions are typical of acid mine drainage processes [25,26]. Note that pyrite oxidation in the numerical model is calculated under the kinetic law defined in the PHREEQC database [27].

### 3. Results

Fig. 3 shows the pH evolution inside the lower reservoir and at downgradient distances of 5, 15, 30 and 45 m from the underground reservoir. The pH decreases abruptly during the first cycles from the initial pH ( $\approx 7$ ) to 3 inside the underground reservoir and 5 m downgradient. After that, the pH continues decreasing more smoothly reaching a value of 2.4 after 30 days. The pH also decreases farther but logically the delay needed for the pH starting to decrease is longer with the distance. In the same manner, the pH reduction is smaller at longer distances. At 15 m the pH starts to decrease after 1.5 days and reaches a value of 4 after 30 days of activity, whilst at 30 m the pH starts to decrease after 10-15 days and reaches a value of 6.4. Finally, at 45 m the reduction of the pH can be considered as negligible. More time is probably needed to observe the impact of the UPSH plant at such distance and farther. Oscillations observed in the results are produced by the simulated pumpings and injections.

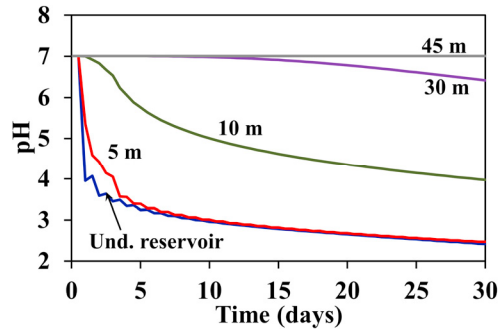


Fig. 3. Simulated pH evolution in the underground reservoir and at 4 different downgradient distances (5, 10, 30 and 45 m).

The simulated pH evolution in the porous medium can be also observed in Fig. 4 that displays the pH distribution in the downgradient direction from the underground reservoir at different simulation times (1, 15 and 30 days). These results are shown for a horizontal section located at 104 m depth.

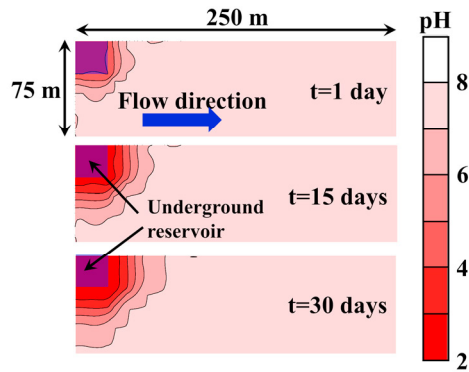


Fig. 4. Simulated horizontal pH distribution at a 104 m depth and in the downgradient direction after 1, 15 and 30 days.

As mentioned previously, a sensitive analysis is performed to check that the dispersivity value attributed in the underground reservoir does not influence the calculated results too much. Fig. 5 shows the pH evolution at a downgradient distance of 5 m from the underground reservoir for two scenarios with dispersivity values of  $10^4$  and 10 m, respectively. As expected, the influence of the dispersivity in the underground reservoir is negligible.

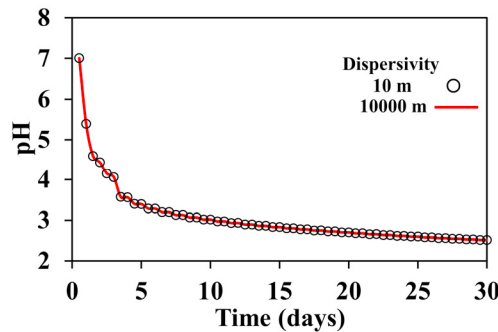


Fig. 5. Simulated pH evolution in the porous medium at a downgradient distance of 5 m from the underground reservoir. Results are shown for contrasted dispersivity values of  $10^4$  and 10 m in the underground reservoir.

#### 4. Discussion and conclusions

The observed behavior in Fig. 3 and Fig. 4 is coherent with the reactions expected since the increment of  $pO_2$  promotes pyrite oxidation when water is released into the underground reservoir. UPSH related activities imply thus a continuous input of  $O_2$ , which is totally consumed for pyrite oxidation, in the underground reservoir and surrounding porous medium. As a consequence, the pH will decrease until the pyrite in the surrounding porous medium is totally consumed. The required time to consume all the pyrite in the vicinity of the underground reservoir will depend on several factors such as the percentage of pyrite, the volume of pumped and injected water and/or the hydraulic parameters of the porous medium. Anyway, the required time may be very long (from decades to centuries).

Results show that UPSH can affect the groundwater quality by decreasing the pH. In addition, pH of water pumped and stored in the upper reservoir will also decrease with time. Thus, water quality of surface water streams may be affected if some overflow water stored in the upper reservoir is released into them. This possibility exists given the progressive filling of the underground reservoir by groundwater seepage inflows. Note that the pyrite dissolution in the vicinity of the underground reservoir could increase slightly the hydraulic conductivity and the storage coefficient (i.e., effective drainage porosity) of the surrounding porous medium. Consequently, groundwater exchanges between the underground reservoir and the surrounding porous medium, and thus, the potential impacts on the groundwater could also be increased. On the other hand, increased water exchanges induced by pyrite dissolution could have a positive influence on the pumps and turbines efficiency [12]. However, more negative effects could be predicted as low values of pH may corrode UPSH facilities.

This work shows that, for the design of future UPSH plants, it will be essential to estimate hydrochemistry related issues, especially in coal mined contexts where the presence of sulfides is common. Predictions using reactive transport modelling are useful to estimate the groundwater quality evolution in and around UPSH systems. However, a detailed case-specific geological and hydrogeological characterization will be needed in real cases to obtain reliable predictions.

#### Acknowledgements

E. Pujades and A. Jurado gratefully acknowledge the financial support from the University of Liège and the EU through the Marie Curie BeIPD-COFUND postdoctoral fellowship programme (2014/16 and 2015/17 fellows from “FP7-MSCA-COFUND, 600405”). This research has been supported by the Public Service of Wallonia – Department of Energy and Sustainable Building.

#### References

- [1] Okazaki, Toru, Yasuyuki Shirai, and Taketsune Nakamura. (2015) "Concept study of wind power utilizing direct thermal energy conversion and thermal energy storage." *Renewable Energy* 83 (2015): 332-338.
- [2] Athari, M. H., and M. M. Ardehali. (2016) "Operational performance of energy storage as function of electricity prices for on-grid hybrid renewable energy system by optimized fuzzy logic controller." *Renewable Energy* 85 (2016): 890-902.
- [3] Giordano, N., C. Comina, G. Mandrone, and A. Cagni. (2016) "Borehole thermal energy storage (BTES). First results from the injection phase of a living lab in Torino (NW Italy)." *Renewable Energy* 86 (2016): 993-1008.
- [4] Hu, Yuan, Zhaohong Bie, Tao Ding, and Yanling Lin. (2016) "An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning." *Applied Energy* 167 (2016): 280-293.
- [5] Mileva, Ana, Josiah Johnston, James H. Nelson, and Daniel M. Kammen. (2016) "Power system balancing for deep decarbonization of the electricity sector." *Applied Energy* 162 (2016): 1001-1009.
- [6] Gebretsadik, Yohannes, Charles Fant, Kenneth Strzepek, and Channing Arndt. (2016) "Optimized reservoir operation model of regional wind and hydro power integration case study: Zambezi basin and South Africa." *Applied Energy* 161 (2016): 574-582.
- [7] Uddin, Nasim, and M. Asce. (2003) "Preliminary design of an underground reservoir for pumped storage." *Geotechnical and Geological Engineering* 21.4 (2003): 331-355.
- [8] Barnes, Frank S., and Jonah G. Levine. (2011) "Large energy storage systems handbook." (2011).

- [9] Pujades, Estanislao, Thibault Willems, Sarah Bodeux, Philippe Orban, and Alain Dassargues. (2016) "Underground pumped storage hydroelectricity using abandoned works (deep mines or open pits) and the impact on groundwater flow." *Hydrogeology Journal* 24, no. 6 (2016): 1531-1546.
- [10] Bodeux, Sarah, Estanislao Pujades, Philippe Orban, Serge Brouyère, and Alain Dassargues. (2017) "Interactions between groundwater and the cavity of an old slate mine used as lower reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): A modelling approach." *Engineering Geology* 217 (2017): 71-80.
- [11] Bodeux, Sarah., Estanislao Pujades, Philippe Orban, Serge Brouyère, Alain Dassargues. (2016) "How groundwater interactions can influence UPSH (Underground Pumping Storage Hydroelectricity) operations", in: Sustainable Hydraulics in the Era of Global Change. CRC Press, pp. 973–973. doi:10.1201/b21902-160
- [12] Pujades, Estanislao, Philippe Orban, Sarah Bodeux, Pierre Archambeau, Sébastien Erpicum, and Alain Dassargues. (2017) "Underground pumped storage hydropower plants using open pit mines: How do groundwater exchanges influence the efficiency?". *Applied Energy* 190 (2017): 135-146.
- [13] Younger, Paul L., Steven A. Banwart, and Robert S. Hedin. (2002) "Mine Water Hydrology." In: *Mine Water: Hydrology, Pollution, Remediation*. Springer Netherlands, 2002. 127-270.
- [14] Bigham, J. M., and D. Kirk Nordstrom. (2000) "Iron and aluminum hydroxysulfates from acid sulfate waters." *Reviews in mineralogy and geochemistry* 40.1 (2000): 351-403.
- [15] Water Framework Directive, Water Framework Directive, 2000/60/EC. Eur. Commun. Off. J.; L327.22.12.2000
- [16] Parkhurst, D. L., Peter Engesgaard, and K. L. Kipp. (1995) "Coupling the geochemical model PHREEQC with a 3D multi-component solute transport model." Fifth Annual VM Goldschmidt Conference. USA: Geochemical Society, Penn State University, University Park. 1995.
- [17] Parkhurst, David L., and Kenneth L. Kipp. (2002) "Parallel processing for PHAST: a three-dimensional reactive-transport simulator." In: *Developments in Water Science*, 47 (2002): 711-718.
- [18] Parkhurst, David L., Kenneth L. Kipp and Scott R. Charlton. (2010) "PHAST Version 2—A Program for Simulating Groundwater Flow, Solute Transport, and Multicomponent Geochemical Reactions". U.S. Geological Survey Techniques and Methods 6–A35.
- [19] Parkhurst, David .L. (1995) "User's guide to PHREEQC—a computer program for speciation, reaction-path, advective transport, and inverse geochemical calculations." US Geological Survey Water Resources graphical user interface for the geochemical computer program Investigations Report.
- [20] Parkhurst, David .L. and C.A.J. Appelo. (1999) "User's guide to PHREEQC (Version 2): A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations."
- [21] Kipp, K.L., 1987. "HST3D; a computer code for simulation of heat and solute transport in three-dimensional ground-water flow systems."
- [22] Kipp, K.L., 1997. "Guide to the Revised Heat and Solute Transport Simulator: HST3D Version 2. "
- [23] Akcil, Ata, and Soner Koldas. (2006) "Acid Mine Drainage (AMD): causes, treatment and case studies." *Journal of Cleaner Production* 14.12 (2006): 1139-1145.
- [24] Sánchez-España, Javier, Iñaki Yusta, and Marta Diez-Ercilla. (2011) "Schwertmannite and hydrobasaluminite: a re-evaluation of their solubility and control on the iron and aluminium concentration in acidic pit lakes." *Applied Geochemistry* 26.9 (2011): 1752-1774.
- [25] Banks, David, Paul L. Younger, Rolf-Tore Arnesen, Egil R. Iversen, and Sheila B. Banks. (1997) "Mine-water chemistry: the good, the bad and the ugly." *Environmental Geology* 32.3 (1997): 157-174.
- [26] Robb, Gordon A. (1994) "Environmental consequences of coal mine closure." *Geographical Journal* (1994): 33-40.
- [27] Williamson, Mark A., and J. Donald Rimstidt. (1994) "The kinetics and electrochemical rate-determining step of aqueous pyrite oxidation." *Geochimica et Cosmochimica Acta* 58.24 (1994): 5443-5454.