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Underground pumped storage hydropower plants using open pit mines: How do groundwater exchanges influence the efficiency?

Estanislao Pujades [a,*], Philippe Orban [a], Sarah Bodeux [a], Pierre Archambeau [b], Sébastien Erpicum [b], Alain Dassargues [a]

[a] Hydrogeology and Environmental Geology, Geo3, Dpt ArGEnCo, Aquapole, University of Liege, 4000 Liege, Belgium
[b] Hydraulics in Environmental and Civil Engineering (HECE), Dpt ArGEnCo, Aquapole, University of Liege, 4000 Liege, Belgium

HIGHLIGHTS

- UPSH allows storing (and producing) large amounts of energy in flat regions.
- UPSH plants interact with the surrounding porous media exchanging water.
- Water exchanges influence the head difference between reservoirs.
- Efficiency of UPSH plants is affected by the water exchanges.
- Higher water exchanges improve the efficiency of pumps and turbines.

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ABSTRACT

Underground Pumped Storage Hydropower (UPSH) is a potential alternative to manage electricity production in flat regions. UPSH plants will interact with the surrounding porous medium through exchanges of groundwater. These exchanges may impact the surrounding aquifers, but they may also influence the efficiency of the pumps and turbines because affecting the head difference between the reservoirs. Despite the relevance for an accurate efficiency assessment, the influence of the groundwater exchanges has not been previously addressed.

A numerical study of a synthetic case is presented to highlight the importance of considering the groundwater exchanges with the surrounding porous medium. The general methodology is designed in order to be further applied in the decision making of future UPSH plants introducing each case specific complexity. The underground reservoir of a hypothetical UPSH plant, which consists in an open pit mine, is considered and modelled together with the surrounding porous medium. Several scenarios with different characteristics are simulated and their results are compared in terms of (1) head difference between the upper and lower reservoirs and (2) efficiency by considering the theoretical performance curves of a pump and a turbine. The results show that the efficiency is improved when the groundwater exchanges increase. Thus, the highest efficiencies will be reached when (1) the underground reservoir is located in a transmissive porous medium and (2) the walls of the open pit mine do not constrain the groundwater exchanges (they are not waterproofed). However, a compromise must be found because the characteristics that increase the efficiency also increase the environmental impacts. Meaningful and reliable results are computed in relation to the characteristics of the intermittent and expected stops of UPSH plants. The frequency of pumping and injection must be considered to properly configure the pumps and turbines of future UPSH plants. If not, pumps and turbines could operate far from their best efficiency conditions.

1. Introduction

Over 81% of the total energy consumed in the world, of which ≈58% is represented by electricity generation in the countries members of the Organisation for Economic Co-operation and Development (OECD), is obtained from fossil fuels [1]. This depen-

* Corresponding author.
E-mail addresses: estanislao.pujades@gmail.com, estanislao.pujades@ulg.ac.be (E. Pujades).

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dence is not sustainable because fossil fuels are limited and impact the environment (e.g., the greenhouse effect). It is therefore necessary to develop renewable sources of energy to replace the electricity obtained from fossil fuels in the near future.

The most important concern with respect to some forms of renewable energy, such as solar and wind energies, is their intermittence and the fact that their production over time cannot be matched to variations in demand [2–6]. Therefore, energy storage systems have become the key to improve the efficiency of renewable energy and increase its utilization [7]. Energy storage systems allow the production of electricity to be managed according to the demand [8,9]. These systems allow the excess energy to be stored during low demand periods and producing electricity when the demand increases.

Pumped Storage Hydropower (PSH) is one of the most commonly used storage systems [10] because it allows large amounts of electricity to be stored and produced [11]. PSH plants, which consist of two reservoirs located at different heights, allow a large percentage (≈70%) of the excess electricity generated during the low demand periods to be reused [12]. However, PSH technology is constrained by topography and land availability because it requires a minimum elevation difference between the two reservoirs as well as large volumes [13]. In addition, PSH plants are controversial due to their impacts on landscape, land use, environment (vegetation and wildlife) and society (relocations) [14,15].

Conversely, Underground Pumped Storage Hydropower (UPSH) [16] is an alternative to store and manage large amounts of electricity that is not limited by topography. Consequently, more sites are available [17]. UPSH plants consist of two reservoirs; the upper reservoir is located at the surface or at shallow depth, while the lower reservoir is underground. Although the underground reservoir can be drilled [18], the cheapest (and possibly most efficient) alternative consists of using abandoned works, such as deep or open pit mines [19,20]. Impacts on land use, vegetation and wildlife produced by UPSH are lower than those of PSH because (at least) one of the reservoirs is underground. However, it is needed to consider the effects of UPSH plants on surrounding porous media to quantify the total environmental impact. Social impacts of UPSH plants are also lower because (1) less relocations are required (the lower reservoir is underground) and (2) the reuse of abandoned mines contributes adding value to local communities after the cessation of mining activities. In addition, sedimentation problems should be also lower in UPSH plants because used groundwater is filtered by the porous medium. Sedimentation problems could probably appear by eroded materials from the open pit walls.

Despite of the benefits, there are no bibliographic evidence of UPSH plants constructed. However, some studies and projects have been mentioned and developed until now. During 1980′s a project to install an UPSH plant was launched in the Netherlands [21], but the plant was not finally constructed for different reasons such as the inadequate characteristics of the soil [22]. Wong [14] assessed the possibility of construct UPSH plants in Singapore using abandoned rock quarries as upper reservoirs. In this case, Wong [14] proposed to drill tunnels or shafts to be used as underground reservoirs. Severson [23] evaluated the potential of ten sites to stablish an underground taconite mine in Minnesota (USA) whose cavity would be after used as lower reservoir for an UPSH plant. Some preliminary studies have been also carried out in Germany to assess the possibilities for construct UPSH plants on abandoned mines in the Harz and Ruhr regions [24–26]. Finally, Spriet [22] explored the possibility for constructing an UPSH plant in Martelange (Belgium).

Underground works are rarely isolated, and groundwater exchanges between UPSH plants and the surrounding porous medium will occur if they are used as underground reservoirs. In addition to the impacts on groundwater levels [20,27], groundwater exchanges may affect the efficiency of UPSH plants. The efficiency of the pumps and turbines depends on the head difference between the upper and the lower reservoirs. This head difference, which varies over time and can be easily predicted in PSH plants (i.e. with waterproof reservoirs), may be influenced by the groundwater exchanges in UPSH plants. Therefore, it is crucial to determine the influence of these exchanges on the head difference between the reservoirs and consequently on UPSH efficiency. This would allow the efficiency of future UPSH plants to be improved by selecting pumps and turbines adapted to the effective groundwater exchanges with the surrounding porous medium. However, no studies in the literature have focused on this issue.

In this study, a synthetic case of an UPSH plant that utilizes an open pit mine as underground reservoir is considered, and the relationship between the groundwater exchanges and the efficiency of the pumps and turbines is studied numerically. The influence of groundwater exchanges on the efficiency and how this varies depending on the system properties (porous medium parameters, open pit mine characteristics and pumping/injection features) are investigated. The main objective is to highlight the paramount importance of considering groundwater exchanges during the design stage of future UPSH plants.

2. Materials and methods

2.1. Problem statement

The problem is formulated as shown in Fig. 1. A hypothetical UPSH plant whose underground reservoir is an open pit mine is considered. Of course, actual properties of open pit mines are more complex, but the goal of the paper is, at this stage, to assess the general relevance of groundwater exchanges in terms of efficiency. Still, some characteristics of the adopted geometry (e.g. the mine flooded depth) are similar to some actual geometries of open pit lakes in Western Europe [28]. The geometry of the open pit mine is conceptually simplified as a square cuboid (top and bottom faces are squares) with a depth of 100 m to facilitate the numerical study while obtaining representative results. This geometrical simplification may affect the volume of groundwater exchanges but not the assessment of their influence on the efficiency of UPSH plants. The initial hydraulic head under natural conditions (without pumping or injection) is located at a depth of 50 m. As a result, half of the open pit is saturated.

The whole thickness (100 m) of the surrounding porous medium is assumed homogeneous and isotropic. The water table is located at a depth of 50 m. Therefore, under natural conditions, it is a 50-m-thick unconfined porous medium. The numerical model has a flat geometry for representing a typical horizontal layered geology. The external boundaries are chosen located at 2500 m from the reservoir to minimize their impact on the simulated evolution of the hydraulic head inside the open pit mine. Their impacts are lower and are later observed as further the boundaries are located. Additional simulations were performed reducing the length of the model to ensure that the flat shape of the modelled domain does not affect the results.

The evolution of the hydraulic head in the underground reservoir is computed to assess the differences between the simulations. Given that the objective is to assess the impact of the groundwater exchanges on the efficiency, a very large and shallow upper reservoir is assumed to eliminate its influence on the results (i.e., the increments of the head difference in the upper reservoir produced by its repeated filling and emptying are neglected). Consequently, the computed head difference is only based on the evolution of the hydraulic head in the underground reservoir.