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Geochemical impacts of groundwater heat pump systems in an urban alluvial aquifer with evaporitic bedrock

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HIGHLIGHTS

- We studied geochemical impacts of groundwater heat pump systems.
- We have sampled a monitoring network in an energetically exploited urban aquifer.
- A limited geochemical interaction has been found in most of the exploitations.
- Reinjection into the aquifer produces an important bedrock gypsum dissolution.
- Scaling in well casing pipes and collapse of the terrain have been observed.

GRAPHICAL ABSTRACT

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ABSTRACT

In the last decade, there has been an extensive use of shallow geothermal exploitations in urban environments. Although the thermal interference between exploitations has been recently studied, there is a lack of knowledge regarding the geochemical impacts of those systems on the aquifers where they are installed. Groundwater flow line scale and well-doublet scale research work has been conducted at city scale to quantify the geochemical interaction of shallow geothermal exploitations with the environment. A comprehensive analysis was conducted on data obtained from a monitoring network specifically designed to control and develop aquifer policies related to thermal management of the aquifer. The geochemical impacts were evaluated from a thermodynamic point of view by means of saturation index (SI) calculations with respect to the different mineral species considered in the system. The results obtained indicate limited geochemical interaction with the urban environment in most of the situations. However, there are some cases where the interaction of the groundwater heat pump installations with the evaporitic bedrock resulted in the total disablement of the exploitation system operation wells. The application of the tool proposed proved to be pragmatic in the evaluation of geochemical impacts. Injection of water into the aquifer can trigger an important bedrock gypsum and halite dissolution process that is partly responsible for scaling in well casing pipes and collapse of the terrain in the vicinity of injection wells.

1. Introduction

As a collective effort of the international community to adapt to and to mitigate climate change drivers (IPCC, 2007; IPCC, 2013), the use of renewable energy technologies is the main strategy adopted worldwide. As a consequence, a total of 78 countries used 121.7 TWh/yr

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(0.44 EJ/yr) of thermal energy directly for heating and cooling purposes in 2008 (Edenhofer et al., 2011). The use of geothermal heat pumps (GHPs) represented 70% of the worldwide installed geothermal heating capacity in 2009 (Lund et al., 2011), where the heat exchange with the subsurface is produced by two main commonly used technologies, depending on the renewability of the fluid used to transport the energy. The first type of installation consists of extracting groundwater to exchange heat directly with it to extract or dissipate heat and then returning it (or not) into the aquifer. Installations using this technology are called open-loop systems or ground water heat pumps (GWHPs). The other type of installation is called closed-loop systems or ground-coupled heat pumps (GCHPs), which use one or more deep vertical boreholes, each containing a heat-exchanger circuit called a borehole heat exchanger (BHE), to exchange heat directly with the ground. The implementation of this technology to exploit shallow geothermal resources has occurred rapidly and worldwide (García-Gil et al., 2014; Lee, 2009; Lienau, 1997; Sanner et al., 2011; Sanner et al., 2003; Yang et al., 2010). On the other hand, this generalized use of GHP systems is endangering the renewability of the resources available, especially in densely populated areas due to the appearance of thermal interferences between exploitations (Epting et al., 2013; Galgaro and Cultrera, 2013; Herbert et al., 2013). Moreover, it has been shown that in a closely packed housing development with single-family homes, only 10% of the heating requirements can be satisfied by GHP systems (Urich et al., 2010).

There are a number of key environmental concerns associated with shallow geothermal systems that have been the focus of various research studies. The fact that these systems are often placed in aquifers that are also used for drinking water wells constitutes a potential risk to groundwater supplies (Bonte et al., 2011). In addition, improperly constructed boreholes could serve as preferential flow paths for contamination, connecting surface and subsurface and/or one aquifer to another. The rate at which thermally altered water is discharged could result in environmental problems such as runoff, erosion of underground strata and structures, and thermal impacts. These potential problems should be taken into account at each stage of the life cycle of a GHP system (*i.e.*, during installation, operation and decommissioning) to avoid such environmental problems (EPA, 1997). Although GWHP systems are non-consumptive (all pumped groundwater is usually returned to the same aquifer from which it was extracted) in most cases, a localized groundwater level rise due to returned or injected waters may also cause tunnel flooding, increased chemical attack on buried steel and concrete, and an increased load on the tunnel lining (Simpson et al., 1989). Few research studies have been published addressing changes in the quality and chemical composition of groundwater affected by the operation of geothermal heat pumps, except for studies investigating processes affecting temperature or, at most, addressing generic issues regarding the physicochemical and negative effects caused by operating these systems (Abesser, 2010; EPA, 1997; Jaudin, 1988). Although these effects are known and described at least from a theoretical point of view, they are actually only considered likely to cause impacts in the return wells (loss of permeability, clogging, etc.). It can be assumed that favorable experiences, or the absence of outstanding impacts in the decades of operation of these types of wells in countries with cold climates, such as those in northern Europe or the US, have contributed to building the idea that the hydrochemical impacts on groundwater are globally negligible. However, the geological and climatic context must be taken into account. Countries with cold climates are often dominated by hard rocks, and the geothermal energy used is primarily focused on heating buildings rather than cooling them. The use of groundwater for cooling involves the use of hot injection wells, which are more reactive with the underground environment.

Due to the shallow geothermal activity, especially in GWHPs, a number of chemical processes, including heterogeneous chemical reactions, have been described as the driving factors for potential problems. These include chemical and biological clogging, abrasion or corrosion of submersible hydraulic pumps, and carbonate and silica scaling in the pipeline and evaporators of heat pumps (Abesser, 2010; Banks, 2012). The changes in groundwater quality due to aquifer thermal energy storage (ATES) have been studied extensively in laboratory experiments (Bonte et al., 2013; Bonte et al., 2014) and in the field (Palmer and Cherry, 1984; Jenne et al., 1992; Brielmann et al., 2011; Jesußek et al., 2012; Vollrath et al., 2013; Zuurbier et al., 2013). In the case of GWHPs, the chemical processes causing problems are essentially the same as those observed in direct recharge or injection wells in artificial recharge installations (Abesser, 2010; Bouwer, 2002). There is a consensus regarding the most sensitive parameters triggering chemical processes affecting GWHP installations and aquifer geochemistry (Brielmann et al., 2009; Brons et al., 1991; Griffioen and Appelo, 1993; Holm et al., 1987; Hoyer et al., 1994): (1) the pH, which can indicate dissolved CO_2 levels, and controls the stability of minerals and the sorption–desorption of dissolved components; (2) the mineral saturation index (SI), which should be used as a convenient indicator of the equilibrium condition of a solution with respect to a considered mineral to predict the presence of reactive minerals and to estimate their reactivities; and (3) the redox potential (Eh), which should be used as the parameter measuring the tendency of the solution to either gain or lose electrons. The latter parameter controls the redox processes and roughly indicates the dissolved oxygen (DO) levels. These parameters can be modified by temperature and pressure changes during the exploitation process. In addition, the Langelier saturation index (LSI) and the Ryznar stability index (RSI) have also been used to predict carbonate scaling inside GWHPs (Cheremisinoff, 1994; Rafferty, 1999).

The influences of GWHPs in the groundwater composition are still being revealed (Park et al., 2015), and long-term monitoring of groundwater geochemistry is necessary to understand the risks involved in the exploitation of shallow geothermal resources.

In this sense, this study focuses on the study of the geochemical impacts associated with 65 GWHP systems operating in the urban environment of Zaragoza City, on an aquifer holding the largest exploitation of geothermal heat pumps in Spain. The hot climate of this southern European country leads to a preferential use of geothermal systems for cooling throughout the year, even in winter. This generates the return of heated waters that permanently produce groundwater pollution. The objectives of this work are (1) to describe the monitoring network specifically designed for the thermal management of the studied aquifer, (2) to perform a geochemical characterization of the urban groundwater body and (3) to evaluate the geochemical impacts induced by GWHPs from a thermodynamic point of view. To do this, the sensitive parameters triggering problematic chemical processes are evaluated at three different scales: at city scale, along a groundwater flow line, and in the proximities of the well doublets of the geothermal systems. Finally, the induced risks related to the solid matrix and bedrock reactivity, scaling, and mineral equilibria are considered in order to investigate the chemical processes involved in the exploitation of shallow geothermal resources using open systems.

2. Study area

In the central sector of the Ebro River basin (Spain), where the confluence of the Gállego and Huerva River tributaries occurs, there is an important alluvial aquifer that is overlain in part by the Metropolitan Area of Zaragoza. Knowledge of the portion of this alluvial aquifer under the city, currently known as the “Urban alluvial Aquifer of Zaragoza” (Garrido et al., 2006; Garrido et al., 2010), has improved since the studies of IGME-DGA (2005); Garrido et al. (2006) and Moreno et al. (2008). The aquifer is composed of two primary sedimentary domains, including Quaternary alluvial terraces related to the Ebro River and its tributaries and a Quaternary alluvial fan area close to the Huerva tributary. The terrace deposits consist of siliceous and carbonate grain-supported gravels, which occur in tabular bodies with cross-bedding structures. The gravels are intercalated with sandy lenticular bodies,