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Recovery of energetically overexploited urban aquifers using surface water

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SUMMARY

Shallow aquifers have an important role in reducing greenhouse gases through helping manage the temperature of urban environments. Nevertheless, the uncontrolled rapid use of shallow groundwater resources to heat or cool urban environments can cause thermal pollution that will limit the long term sustainability of the resource. Therefore, there is a need for appropriate mitigation/remediation strategies capable of recovering energetically overexploited aquifers. In this work, a novel remediation strategy based on surface water recharge into aquifers is presented. To evaluate the capabilities of such measures for effective remediation, this strategy is optimized for a management problem raised in the overheated "Urban Alluvial Aquifer of Zaragoza" (Spain). The application of a transient groundwater flow and heat transport model under 512 different mitigation scenarios has enabled to quantify and discuss the magnitude of the remediation effect as a respond to injection rates of surface water, seasonal schedule of the injection and location of injection. The quantification of the relationship between these variables together with the evaluation of the amount of surface water injected per year in each scenario proposed have provided a better understanding of the system processes and an optimal management alternative. This work also makes awareness of the magnitude of the remediation procedure which is in an order of magnitude of tenths of years.

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions from fossil fuel combustion and industrial processes have contributed to the rising trend in the average global temperature (IPCC, 2007, 2013). The use of renewable energy technologies is the main strategy adopted worldwide toward adaptation and mitigation of climate change drivers (IPCC, 2013). In this context, geothermal energy is used directly for heating and cooling in 78 countries worldwide, generating 121.7 TW h/yr (0.44 EJ/yr) of thermal energy in 2008 (Edenhofer et al., 2011). Direct geothermal use served from Geothermal Heat Pumps (GHP) contributed 70% (35.2 GWth) of the worldwide installed geothermal heating capacity in 2009 and this amount has been doubled every five years since 2000 (Lund et al., 2011; Rybach, 2005).

The increasing surface and subsurface temperatures due to anthropogenic activity and infrastructure in urban areas is known as heat-island effect (Allen et al., 2003; Benz et al., 2015; Ferguson and Woodbury, 2007; Taniguchi et al., 2005; Zhu et al., 2011). The amount of heat released into the groundwater from the cities is mainly transferred indirectly by thermal diffusion from subsurface and surface structures, and directly by shallow geothermal resources exploitation. The result is, in many cases, a severe impacted thermal regime of aquifers. Moreover, the heated groundwater is transported according to existent groundwater flow patterns. This situation highlights a complicated framework which is getting more complex as city development increases and GHP systems are one of the fastest growing applications of renewable energy (Lund et al., 2011). Thermal interferences between shallow geothermal exploitations together with scarce or non-existent normative framework represent important barriers to the implementation of this technology in cities (Jaudin, 2013). Important issues affecting future utilization include energy sustainability and, therefore the thermal management of the resources available. Thermal management of shallow resources is critical when there is unbalanced use, i.e., when the heating or cooling demand has a significant deviation from one other (especially in cold and hot extreme climates). This deviation modifies the thermal regime of the aquifer and reduces its geothermal potential, even making it disappear. Several authors have

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demonstrated the existence of thermal interferences between shallow geothermal exploitations, thus highlighting the need for corrective measures to prevent the energetic overexploitation of suburban environments (Epting et al., 2013; Galgaro and Cultrera, 2013; García-Gil et al., 2014; Herbert et al., 2013; Urich et al., 2010). This energetic overexploitation complicates the development of shallow geothermal allocation plans. In general, the requirement of optimization procedures as a tool for restoring groundwater resources has been the subject of classical research since the 1960s (Gorelick, 1983; Singh, 2014b; Wagner, 1995). Solving the optimization problems allows to obtain the best management strategy under consideration of the management objectives and constraints. This results in the prevention or reduction of loss of groundwater resources from damaging processes such as saltwater intrusion (Abarca et al., 2006; Cheng et al., 2000; Dhar and Datta, 2009; Singh, 2014a), dewatering excavation areas (Epting et al., 2008; Jiang et al., 2013), generation of contamination plumes (Andricevic and Kitanidis, 1990; Cardiff et al., 2010; Yang et al., 2013b), unsustainable water supplies (Fragoso et al., 2009; Xu et al., 2013; Yang et al., 2013a) and others (Chau, 1992; Eusuff and Lansey, 2004), which have been the subject of much research. Most of these studies highlight the success of using aquifer simulation models combined with optimization techniques to address groundwater management alternatives and to obtain a particularly optimal technique.

In this context, (Epting and Huggenberger, 2013) defined the potential natural state of a groundwater body and proposed the first remediation strategies for an overheated urban groundwater body. These strategies consisted in the active injection of cooled water (well doublet) from new GHP installations exploiting shallow geothermal resources for heating purposes in winter (Epting et al., 2013). Numerical modeling results obtained show and expand the cooling influence of recovering down-gradient thermal equilibria in the area. In this paper, a novel strategy based on the artificial increase of surface water recharge by using injection wells is proposed for the recovery of the potential natural state of urban groundwater bodies currently energetically overexploited. The complex response of the aquifer and existing exploitations systems to the surface water injection results in an optimization problem where temperature constraints are not linearly related to the decision variables. The application of the finite element method to groundwater flow and heat transport equations has permitted the exploration of thermal management alternatives under various design scenarios, including location of injection, seasonal recharge and injection rates. This has allowed the minimization of surface water injection to mitigate thermal contamination caused by intensive exploitation of shallow geothermal resources. The aim of this work is to (1) present a novel corrective measure to enhance the recovery of energetically overexploited aquifers using surface water, (2) perform an analysis of the main variables constraining the nonlinear optimization problem to design a specific remediation strategy useful to local administrators and (3) discuss the results obtained from the application of the proposed corrective measure to a real case of an overheated urban aquifer in the city of Zaragoza (Spain).

2. Problem statement

2.1. Hydrogeological setting

The city of Zaragoza is located on the confluence of the rivers Ebro, Gállego and Huerva in the central sector of the Ebro basin (Fig. 1). The Quaternary alluvial sediments deposited by these rivers configure the most important aquifer in the region named in previous works as "Ebro alluvial Aquifer" (Garrido et al., 2006, 2010). From a stratigraphic perspective, two main sedimentary domains can be distinguished in this one-layer aquifer corresponding to Quaternary alluvial terraces and a Quaternary alluvial fan area in genetic relation with the Huerva tributary. The terrace deposits present channel facies with grain-supported siliceous and carbonate gravels. These terrace deposits conform to sedimentary bodies up to several meters in thickness and extend laterally 100 m or more. Generally, they are tabular bodies with internal cross-bedding. Locally, channel bodies might present dominant trough cross-bedding and/or intercalated sandy lenticular bodies

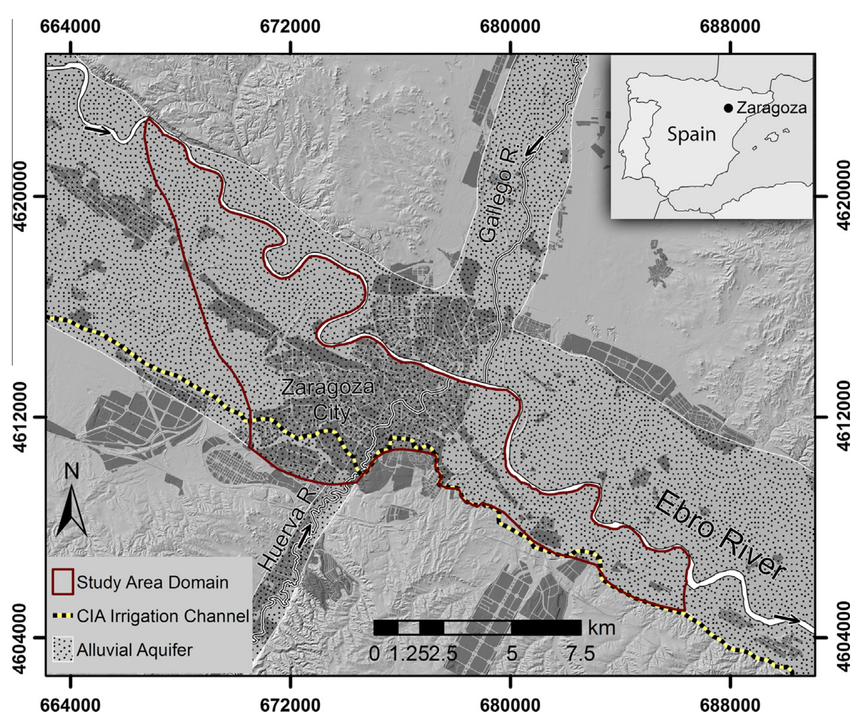

Fig. 1. Location and main hydrogeological features of the investigated area. Projection: WGS 1984 Complex UTM Zone 30 N, Datum DWGS1984.