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The thermal consequences of river-level variations in an urban groundwater body highly affected by groundwater heat pumps

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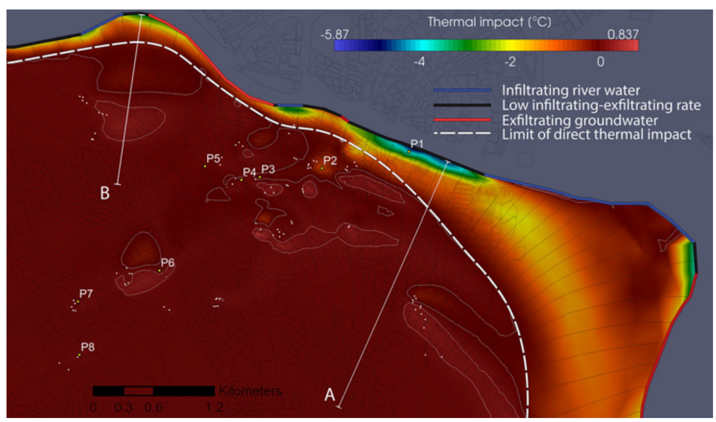
HIGHLIGHTS

- Thermal impact of river water recharges induced by flood events
- Urban groundwater body highly affected by groundwater heat pumps
- Geothermal management of alluvial urban aquifers
- Variable direct thermal impact along the river trajectory
- Minor indirect thermal impacts due to hydraulic gradient variations

GRAPHICAL ABSTRACT



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ABSTRACT

The extensive implementation of ground source heat pumps in urban aquifers is an important issue related to groundwater quality and the future economic feasibility of existent geothermal installations. Although many cities are in the immediate vicinity of large rivers, little is known about the thermal river–groundwater interaction at a kilometric-scale. The aim of this work is to evaluate the thermal impact of river water recharges induced by flood events into an urban alluvial aquifer anthropogenically influenced by geothermal exploitations. The present thermal state of an urban aquifer at a regional scale, including 27 groundwater heat pump installations, has been evaluated. The thermal impacts of these installations in the aquifer together with the thermal impacts from "cold" winter floods have also been spatially and temporally evaluated to ensure better geothermal management of the aquifer. The results showed a variable direct thermal impact from 0 to 6 °C depending on the groundwater–surface water interaction along the river trajectory. The thermal plumes far away from the riverbed also present minor indirect thermal impacts due to hydraulic gradient variations.

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1. Introduction

Since the first decades of the twentieth century, ground-source heat pump (GSHP) systems have been considered to be an effective technology for refrigeration and environmental comfort. The technology's environmental friendliness coupled with a global awareness of anthropogenic climate change explains the current high frequency of GSHP installations. Today, the total number of GSHP systems exceeds 1 million, and in Europe, more than 100,000 TJ are saving approximately 3.7 Mt of CO_2 emissions (Bayer et al., 2012). Moreover, GSHP systems are the most important direct geothermal application throughout the world; in 2005, they constitute 54.4% of all geothermal systems (Lund et al., 2011).

There are two main types of GSHP systems. The ground-coupled heat pump (GCHP) systems consist of a heat pump connected to a closed-loop network of thermally fused plastic piping that is buried in the ground. A water antifreeze solution is circulated through the inside of the pipe network transferring heat from the ground to the heat exchanger. No groundwater enters the pipe network; only heat is transferred by conduction to the refrigerant. Groundwater heat pumps (GWHPs), the second subset of GSHP systems, directly exploit the significant heat capacity of groundwater. Using an extraction (or production) well, the water is conducted directly to the heat pump, where heat is added or removed from the water. The heated or cooled water is then returned to the ground through an injection well.

In urban areas, the demand for using water as cheap cooling media is expected to increase, but there are still three main uncertainties that may dissuade investors: thermal short circuits of individual geothermal installations, interactions with other boundary conditions and uncertain legislative developments.

The thermal short circuit of a GWHP system compromises the usable lifetime of the geothermal system. In some cases where the regional groundwater hydraulic gradient is too low in relation to the flow rate of the extraction–injection wells and the lack of space for the doublet well system, a thermal short circuit may occur (Galgaro and Cultrera, 2013). In this case, reinjected water flows towards the extraction well(s), driving up (or down in the case of heating configurations) the production temperature. Therefore, efficiency is reduced over time, and in some cases, a total system failure occurs.

The modification on the different natural and anthropogenic thermal boundaries (environments) may compromise the viability of individual systems. Therefore, the thermal groundwater regimes must be adequately assessed, considering the different thermal boundaries, to calculate the real energy potential.

The surface sealing, subsurface construction and groundwater use represent the major anthropogenic thermal boundary changes. Heated buildings and subsurface infrastructure represent a heat input to the ground that can affect the groundwater temperature, resulting in the urban heat island effect (Ferguson and Woodbury, 2007; Taniguchi et al., 2005; Zhu et al., 2011). In densely urbanized areas in the city of Basel, northwestern Switzerland, groundwater temperatures have increased significantly and have reached 17 °C in an area where the long-term average annual air temperature is approximately 10 °C (Epting et al., 2013). Herbert et al., 2013 documented the thermally impacted state of the city of London due to changes in the groundwater use. With 70 GW h of ground-sourced energy capacity installed, 2.9% of central London was impacted by thermal plumes. The interference between GWHPs associated with the high density of geothermal systems installed was also described.

Seasonal atmospheric temperature changes (Händel et al., 2013; Pouloupatis et al., 2011), climate change (Epting and Huggenberger, 2013), and river–groundwater interactions are natural thermal phenomena that may play a role in the groundwater thermal regime and hence in the thermal management of exploited geothermal aquifers. The monitoring of temperatures in wells more than 190 m from the Columbia River (Washington State, U.S.A.) has shown that high and low river stages influence the groundwater temperature (Fritz et al., 2007). In some cases, the river–groundwater temperature interaction was ignored because of the objectives of the investigations (e.g., Freedman et al., 2012), whereas in others, it was considered in daily intervals of head and river water temperature (Epting et al., 2013). Although temperature has been used as a tracer to estimate recharge from surface waters (Anderson, 2005; Engelhardt et al., 2011; Hyun et al., 2011; Vázquez-Suñé et al., 2007), there has still been no investigation that has focused on the magnitude and distribution of the thermal impacts induced by flood events in an urban aquifer with intensive geothermal exploitation.

Although there have been several experimental (Bi et al., 2002; Lo Russo and Civita, 2009; Russo et al., 2011) and theoretical (Banks, 2009; Diao et al., 2004; Molina-Giraldo et al., 2011; Zeng et al., 2003) investigations studying the performance and design of GSHP systems, administrative regulations that restrict groundwater thermal regime changes are still evolving. In some cases, regulatory requirements address the hydraulic consequences of the geothermal system rather than potential thermal impacts, or in other cases, only a technical report with minimal hydrogeological input is required (Banks, 2009). A 2010 study by the National Ground Water Association (NGWA, 2010) concluded that only 4% of state regulation agencies in the U.S.A. demanded heat transfer calculations. In Europe, governmental environmental agencies occasionally restrict the temperature change in relation to the background temperature, e.g., 3 °C at 100 m from the heat exchange point in the case of Switzerland (GSchV, 2001). In Austria (Händel et al., 2013), a 6 °C temperature change is permitted with injection temperatures between 5 and 20 °C. More information related to the legal status of the use of shallow geothermal energy can be found in the literature (Haehnlein et al., 2010). It is clear that the thermal impacts and the lack of regulations reveal the need for an exploitation scheme regulated by water administrations. Current regulations adopted dealing with individual schemes in isolated exploitations are necessary but not sufficient. For a complete perspective on the problem, it is feasible and prudent to manage the thermal resources using an energy resource model for the whole aquifer (Herbert et al., 2013).

There is a general agreement (e.g., Baccino Giorgia et al., 2010; Florides and Kalogirou, 2007; Liang et al., 2011) about the need to record thermal changes and impacts to protect the urban aquifer environment and guarantee production temperatures for existing geothermal systems. Starting with adequate monitoring systems, analytical and numerical methods are able to reproduce heat transport processes induced by GWHP systems, and they can therefore be used as important tools to assess the thermal impact and performance and design issues of geothermal devices. Banks (2009) presented an analytical solution for assessing thermal impacts derived from open-loop doublet designs. Due to the variety of well designs, the heterogeneity of aquifers and variable heating–cooling loads, it was concluded that better approaches are achieved with numerical models (Banks, 2009). However, those numerical approaches have two main limitations: the initial data quality and the large amount of time required.

The heat transport models use regional models to predict the behavior and impact of geothermal systems (Händel et al., 2013) and to enable (Epting et al., 2013) the development of the first thermal management strategies. In those works, the concepts of adaptive resource management and shallow thermal groundwater use in urban areas were introduced for the first time.

This paper aims to use high-resolution monitoring and coupled groundwater and heat-flow models as useful tools to evaluate the importance of the river–groundwater thermal boundary in an urban aquifer. This natural thermal interaction is responsible for the aquifer recharge (up to 20 m^3 day^{-1} per river bed meter at a temperature ranging from 4 to 10 °C) induced by river flood events in the urban aquifer of Zaragoza, Spain. Spatially, 8.5 km^2 are anthropogenically heated by geothermal systems, and temperatures in some locations exceed 30 °C at injection points. A characterization of the present thermal state of