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Advection and dispersion heat transport mechanisms in the quantification of shallow geothermal resources and associated environmental impacts

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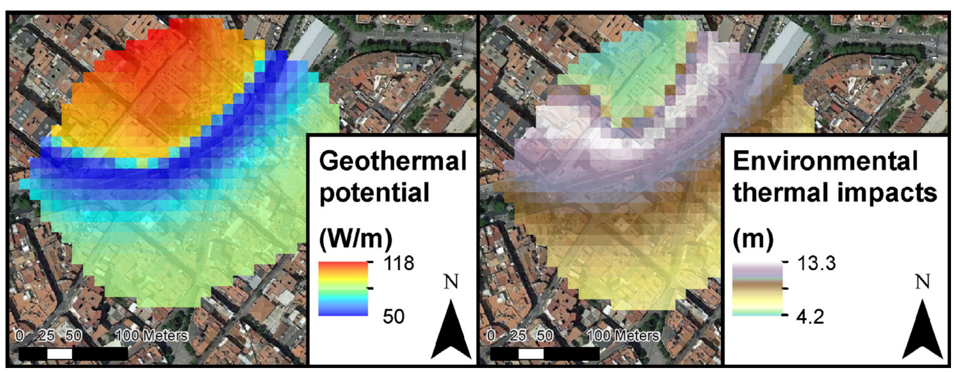
HIGHLIGHTS

- A GIS methodology is presented for the management of shallow geothermal energy.
- Shallow geothermal potential is estimated on a regional scale.
- Environmental impacts associated with shallow geothermal energy are quantified.
- The transient thermal state is modeled with advection and dispersion mechanisms.

GRAPHICAL ABSTRACT



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ABSTRACT

Borehole Heat Exchangers (BHEs) are increasingly being used to exploit shallow geothermal energy. This paper presents a new methodology to provide a response to the need for a regional quantification of the geothermal potential that can be extracted by BHEs and the associated environmental impacts. A set of analytical solutions facilitates accurate calculation of the heat exchange of BHEs with the ground and its environmental impacts. For the first time, advection and dispersion heat transport mechanisms and the temporal evolution from the start of operation of the BHE are taken into account in the regional estimation of shallow geothermal resources. This methodology is integrated in a GIS environment, which facilitates the management of input and output data at a regional scale. An example of the methodology's application is presented for Barcelona, in Spain. As a result of the application, it is possible to show the strengths and improvements of this methodology in the development of potential maps of low temperature geothermal energy as well as maps of environmental impacts. The minimum and maximum energy potential values for the study site are 50 and 1800 W/m^2 for a drilled depth of 100 m, proportionally to Darcy velocity. Regarding to thermal impacts, the higher the groundwater velocity and the energy potential, the higher the size of the thermal plume after 6 months of exploitation, whose length ranges from 10 to

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27 m long. A sensitivity analysis was carried out in the calculation of heat exchange rate and its impacts for different scenarios and for a wide range of Darcy velocities. The results of this analysis lead to the conclusion that the consideration of dispersion effects and temporal evolution of the exploitation prevent significant differences up to a factor 2.5 in the heat exchange rate accuracy and up to several orders of magnitude in the impacts generated.

1. Introduction

Low Temperature Geothermal Energy (LTGE), also known as shallow geothermal energy, is the energy accumulated in the ground available for heat exchange with an external medium at low temperature. The exploitation of LTGE consists of exchanging heat between the ground and any installation or building that needs heat or to dissipate it.

Commercial use of LTGE has expanded greatly during the last decade (for further details see Gemelli et al., 2011) because it provides an alternative energy source with several advantages over other renewable energies, such as: (1) the lowest environmental impact of any renewable energy source, (2) high availability regardless of weather conditions, (3) decentralized and localized production and (4) economic viability. Thus, an accurate assessment of the potential and impacts of LTGE is paramount for the development of effective renewable energy strategies (Goodman et al., 2004; Busby et al., 2009; Epting and Huggenberger, 2013; García-Gil et al., 2014). However, there are still countries in Europe where energy strategies involving LTGE are not yet sufficiently developed despite its advantages. To promote the use of LTGE it is necessary to provide the decision-makers or the stakeholders with the quantification of the Low Temperature Geothermal Potential (LTGP) at a regional scale together with the assessment of the environmental impact produced by its exploitation.

To assess the potential energy exchange of the ground, the main heat transport mechanisms should be considered: advection and dispersion. In general terms, many authors have highlighted the relevance of groundwater flow when estimating LTGP (Chiasson et al., 2000; Wang et al., 2009; Choi et al., 2013; Angelotti et al., 2014). Ignoring the contribution of advection in heat transport may lead to oversized shallow geothermal exploitation systems (Fan et al., 2007). In addition, Molina-Giraldo et al. (2011) and Hidalgo et al. (2009) remarked on the importance of dispersion when estimating thermal impacts at regional scales, especially for medium sand to gravel aquifers.

Numerical modeling is an optimal solution that takes the main heat transport mechanisms into consideration. However, such models usually involve high computational costs (Lee and Lam, 2012; Pearson et al., 2013; Angelotti et al., 2014; Ozudogru et al., 2014). Additionally, these models often solve the heat problem only for particular configurations of a thermal exploitation. Only Fujii et al. (2007) used the numerical modeling to generate a regional map of LTGP. Their methodology was based on calculating LTGP for several locations in their study area. They accomplished their calculations by generating individual numerical models for each location. Following spatial interpolation, a spatial distribution map of LTGP was generated.

As an alternative to numerical modeling, several analytical models have been developed assuming different boundary conditions (for an update on this technique, see Abdelaziz et al., 2014). Nevertheless, as usually occurs with numerical models, analytical models aim to solve the geothermal problem for specific local-scale applications.

At a regional scale, Geographic Information Systems (GIS) are an effective platform for managing existing geological, hydrogeological and renewable energy data (Strassberg et al., 2007; Domínguez and Amador, 2007; Voivontas et al., 1998). The GIS environment is also useful for developing an integrated geological and hydrogeological conceptual model, required for the estimation of LTGP. As Blum et al. (2011) remarked, GIS-supported maps of shallow geothermal systems may help to characterize the subsurface media when dimensioning exploitations, to avoid under- or oversizing.

However, the GIS-based applications and methodologies developed for the estimation of LTGP have an empirical character. Hamada et al. (2002) proposed a GIS methodology for evaluating the suitability of LTGP exploitation that created qualitative maps based on underground thermal properties and groundwater characteristics. Ondreka et al. (2007) developed a GIS-based methodology to empirically calculate the LTGP at a regional scale. Their methodology is based on the average specific heat extraction values for each material. Similarly, Gemelli et al. (2011) established a GIS methodology to estimate the economic exploitability of LTGP. In addition to the ground properties, Galgaro et al. (2015) consider the efficiency of the technology and the energy demand to estimate empirically the LTGP. However, none of these authors have considered the effects of groundwater flow. Moreover, these approximations are valid when the geological and hydrogeological models are unreliable or not very precise. With these data available and comprehensive, García-Gil et al. (2015) generated a GIS methodology to assess the LTGP at a regional scale, taking into account groundwater flow, but without considering dispersion. Despite these advantages, none of the aforementioned GIS methodologies consider the temporal evolution of the thermal system, which is especially relevant when geothermal exploitations have a cooling mode in summer and a heating mode in winter.

To overcome the above limitations in estimating LTGP, this paper presents a new methodology integrated in a GIS environment. It focuses on the quantification of LTGP at a regional scale. When necessary, the main heat transport mechanisms—advection and dispersion—can be taken into account to calculate the transient thermal state. A set of maps representing the main variables in shallow geothermal systems can be created, including LTGP maps and maximum distances of thermal disturbance. These maps represent a powerful tool to support decision-making processes concerning shallow groundwater energy resources (Ramachandra and Shruthi, 2007).

2. Methodology

2.1. Previous considerations

Two main types of shallow geothermal exploitation designs are used to exchange heat with the subsurface medium; the first involves closed loop systems, or Ground-Coupled Heat Pumps (GCHP), and the second consists of open loop systems, or Ground Water Heat Pumps (GWHP). The application of Borehole Heat Exchangers (BHEs) in closed systems (for further details, see Yang et al., 2010 and Self et al., 2013), is increasingly being used to draw on LTGE, so the proposed methodology focuses on closed loop vertical borehole heat exchangers. Horizontal shallow geothermal installations are beyond the scope of this research.

BHEs typically consist of one or more 50–100 m deep vertical boreholes with a heat exchanger circuit inside them. This type of exploitation system exchanges heat directly with the ground and immobile groundwater in pores through conduction. When groundwater flow exists, advection and dispersion heat transport mechanisms favor the heat exchange. In the range of temperature variations produced by shallow geothermal energy ($\pm$10 K), the effects on groundwater flow due to variations of kinematic viscosity and density of water can be neglected (Stauffer et al., 2014). So, it is possible to assume that the hydraulic state of the aquifer remains unchanged. However, the thermal regime is disturbed. BHEs are widely used in heating and cooling of commercial