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# Coupling heat and chemical tracer experiments for estimating heat transfer parameters in shallow alluvial aquifers

S. Wildemeersch [a], P. Jamin [a,*], P. Orban [a], T. Hermans [b,1], M. Klepikova [a], F. Nguyen [b],
S. Brouyère [a], A. Dassargues [a]

[a] University of Liege, ArGEnCo, GEO$^3$, Hydrogeology and Environmental Geology, Aquapôle, B52/3 Sart-Tilman, 4000 Liege, Belgium
[b] University of Liege, ArGEnCo, GEO$^3$, Applied Geophysics, B52/3 Sart-Tilman, 4000 Liege, Belgium

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## ABSTRACT

Geothermal energy systems, closed or open, are increasingly considered for heating and/or cooling buildings. The efficiency of such systems depends on the thermal properties of the subsurface. Therefore, feasibility and impact studies performed prior to their installation should include a field characterization of thermal properties and a heat transfer model using parameter values measured in situ. However, there is a lack of in situ experiments and methodology for performing such a field characterization, especially for open systems. This study presents an in situ experiment designed for estimating heat transfer parameters in shallow alluvial aquifers with focus on the specific heat capacity. This experiment consists in simultaneously injecting hot water and a chemical tracer into the aquifer and monitoring the evolution of groundwater temperature and concentration in the recovery well (and possibly in other piezometers located down gradient). Temperature and concentrations are then used for estimating the specific heat capacity. The first method for estimating this parameter is based on a modeling in series of the chemical tracer and temperature breakthrough curves at the recovery well. The second method is based on an energy balance. The values of specific heat capacity estimated for both methods (2.30 and 2.54 MJ/m$^3$/K) for the experimental site in the alluvial aquifer of the Meuse River (Belgium) are almost identical and consistent with values found in the literature. Temperature breakthrough curves in other piezometers are not required for estimating the specific heat capacity. However, they highlight that heat transfer in the alluvial aquifer of the Meuse River is complex and contrasted with different dominant process depending on the depth leading to significant vertical heat exchange between upper and lower part of the aquifer. Furthermore, these temperature breakthrough curves could be included in the calibration of a complex heat transfer model for estimating the entire set of heat transfer parameters and their spatial distribution by inverse modeling.

## 1. Introduction

Geothermal energy is a renewable and sustainable energy source particularly attractive in the current context of environmental protection and fighting against climate change. Consequently, shallow geothermal energy systems are increasingly considered for heating and/or cooling buildings (Lund et al., 2011). The main techniques for exploiting shallow geothermal energy are ground source heat pumps (GSHP), which are closed systems with a horizontal or a vertical heat exchanger, and groundwater heat pumps (GWHP), which are open systems requiring a pair of injection and withdrawal wells or a withdrawal well and a discharge through surface water.

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* Corresponding author. Tel.: +32 43662035; fax: +32 43669520.
*E-mail address:* pierre.jamin@ulg.ac.be (P. Jamin).

[1] F.R.S.-FNRS., Research Fellow, Brussels, Belgium.

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The efficiency of heating systems depends on the hydraulic properties (hydraulic conductivity, porosity, specific yield) and the thermal properties (specific heat capacity, thermal conductivity, and thermal dispersivity) that govern heat transfer in the subsurface. Therefore, prior to their implementation, a feasibility study is recommended. An impact study is also required in some countries to prove compliance of the system with the ongoing regulations (Haehlein et al., 2010). This impact study is important since such systems induce thermal anomalies in the form of cold or heat plumes in groundwater (Molson et al., 1992; Palmer et al., 1992; Warner and Algan, 1984) which may influence groundwater chemistry (e.g. Jesuβek et al., 2013) and microbiology (e.g. Brielmann et al., 2009). This impact study is also important for evaluating the long-term efficiency of the system. These feasibility and impact studies should ideally include a field characterization of the thermal properties of the subsurface and a heat transfer model of the heating system using heat transfer parameter values measured in situ. However, field characterization is often limited and the dimensioning of heating systems is generally based on parameter values found in the literature or on default values of software (e.g. de Paly et al., 2012; Freedman et al., 2012; Lo Russo and Civita, 2009; Lo Russo et al., 2012). This is related to the lack of in situ experiments and methodology available for estimating heat transfer parameters in the subsurface. The thermal response test (TRT) has become very popular for designing closed systems. This test provides an estimation of the effective ground thermal conductivity, including the effects of groundwater flow and natural convection (Gehlin, 2002; Sanner et al., 2005, 2013). The effective ground thermal conductivity is representative for closed systems but not for open systems because the TRT does not take into account the significant influence of withdrawal wells on groundwater flow. Furthermore, the TRT does not provide any estimation of specific heat capacity and thermal dispersivity. Therefore, there is a need for other in situ experiments capable of estimating these parameters. This is particularly important for open systems since heat exchange between the groundwater and the aquifer solids is proportional to the specific heat capacity of the saturated porous medium and it modifies the temperature of the pumped groundwater.

The methodology we propose couples heat and chemical tracer experiments. The originality is to simultaneously inject hot water and a chemical tracer into the aquifer and to monitor the evolution of groundwater temperature and tracer concentration in different piezometers located down gradient (including the recovery well). The coupling with a chemical tracer experiment is performed for taking advantage of the similarities between heat transfer and solute transport in porous media in order to facilitate the separation of heat transfer processes and identify related parameters with focus on specific heat capacity. The effective porosity, in particular, simultaneously governs heat transfer by convection and solute transport by advection. Therefore, this parameter is estimated by fitting the chemical tracer breakthrough curve. Given that the effective porosity is known, the temperature breakthrough curve is used for estimating the thermal retardation factor which is proportional to the specific heat capacity of the saturated porous medium, key parameter governing heat exchange between groundwater and aquifer solids.

The use of heat as a groundwater tracer for estimating hydraulic parameters such as hydraulic conductivity is quite usual (Anderson, 2005). However, only a few studies focus on the use of groundwater temperature for estimating heat transfer parameters (Giambastiani et al., 2013; Vandenbohede et al., 2009, 2011). These studies are interesting since they show the capabilities and the limitations of such experiments. However, they mainly consist in laboratory experiments in a tank (Giambastiani et al., 2013) or in situ experiments with injection of only a small volume of hot water (5.8 $m^3$) (Vandenbohede et al., 2011). Here, we focus on in situ heat tracer experiments with injection of a significant volume of hot water (72 $m^3$) and with a monitoring of the temperature both in the upper and lower parts of the aquifer thanks to a network of double screened piezometers.

A short presentation of the experimental site is followed by a description of the experimental setup and the methodology. The measured breakthrough curves for the temperature and the chemical tracer are then presented, interpreted, and discussed. The paper ends with the conclusions and the perspectives.

## 2. Field site

The experimental site is located in the village of Hermalle-sous-Argenteau, 13 km north-east of the city of Liège in Belgium. The site consists in a vast meadow lying on the alluvial plain of the Meuse River (Fig. 1). The alluvial deposits can be divided into four different units. The upper layer is 1 to 1.5 m thick and is composed of loam with clay lenses. The second unit consists of sandy loam with millimetric gravels which proportion increases with depth down to 3 m depth. From 3 to 10 m below ground surface, the third layer is mainly made of alluvial sand and gravels. The gravels to sand ratio increases progressively with

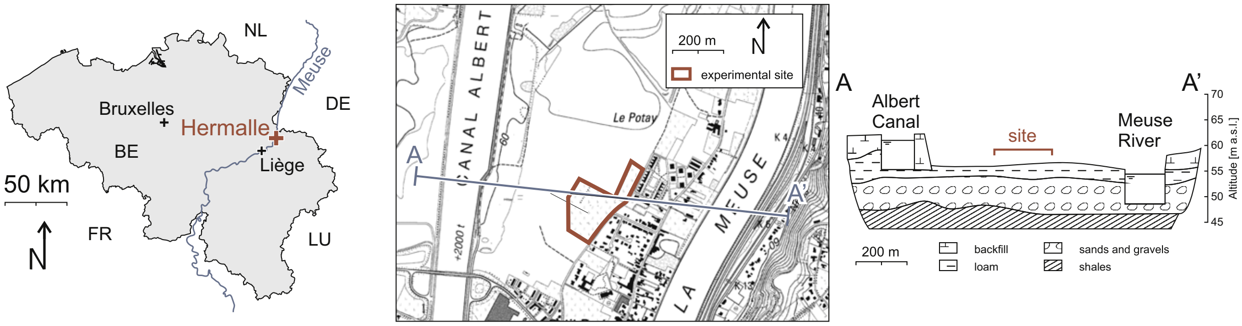

**Fig. 1.** The test site is located 13 km north east of Liège, Belgium, Western Europe, on the alluvial plain of the River Meuse.