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Deterministic modeling of the impact of underground structures on urban groundwater temperature

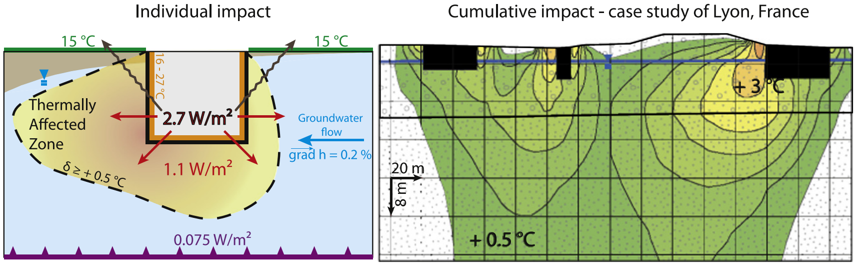
Guillaume Attard [a,b,*], Yvan Rossier [c], Thierry Winiarski [a], Laurent Eisenlohr [b]

[a] *Univ. Lyon, Ecole Nationale des Travaux Publics de l'Etat, LEHNA, UMR CNRS 5023, 3 Rue Maurice Audin, F-69120 Vaulx-en-Velin, France*
[b] *Cerema, 48 Rue Saint Théobald, F-38081 L'Isle d'Abeau, France*
[c] *Univ. Grenoble Alpes, LTHE, Domaine Universitaire, 1381 Rue de la Piscine, 38400 Saint Martin d'Hères, France*

HIGHLIGHTS

- Individual impact of underground structures on groundwater temperature were assessed.
- A Thermal Affected Zone is shown to occur approximately 100 m around the structure.
- The cumulative impact on ground water temperature was assessed in Lyon (France).
- The area impacted represents 10 times the total surface area of structures.
- The total annual heat flow from deep structures represents 4.5 GW · h.

GRAPHICAL ABSTRACT



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ABSTRACT

Underground structures have a major influence on groundwater temperature and have a major contribution on the anthropogenic heat fluxes into urban aquifers. Groundwater temperature is crucial for resource management as it can provide operational sustainability indicators for groundwater quality and geothermal energy. Here, a three dimensional heat transport modeling approach was conducted to quantify the thermally affected zone (TAZ, i.e. increase in temperature of more than +0.5 °C) caused by two common underground structures: (1) an impervious structure and (2) a draining structure. These design techniques consist in (1) ballasting the underground structure in order to resist hydrostatic pressure, or (2) draining the groundwater under the structure in order to remove the hydrostatic pressure. The volume of the TAZ caused by these underground structures was shown to range from 14 to 20 times the volume of the underground structure. Additionally, the cumulative impact of underground structures was assessed under average thermal conditions at the scale of the greater Lyon area (France). The heat island effect caused by underground structures was highlighted in the business center of the city. Increase in temperature of more than +4.5 °C were locally put in evidence. The annual heat flow from underground structures to the urban aquifer was computed deterministically and represents 4.5 GW · h. Considering these impacts, the TAZ of deep underground structures should be taken into account in the geothermal potential mapping. Finally, the amount of heat energy provided should be used as an indicator of heating potential in these areas.

1. Introduction

Half of the world's population now lives in cities. This phenomenon of urbanization is such that this proportion will reach 70% before 2050

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* Corresponding author at: Univ. Lyon, Ecole Nationale des Travaux Publics de l'Etat, LEHNA, UMR CNRS 5023, 3 Rue Maurice Audin, F-69120 Vaulx-en-Velin, France.
E-mail addresses: guillaume.attard@entpe.fr, guillaume.attard@cerema.fr (G. Attard).

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(Un-Habitat, 2008). Land constraints lead to the vertical development of urban areas, with the construction of ever-deeper structures (Bobylev, 2009) (e.g., subways, building foundations, underground carparks). In parallel, the urban subsoil is now recognized as a space rich in resources: available water, geomaterials and geothermal energy (Li et al., 2013b, a), which play a vital role in ensuring sustainable territorial development (Goel et al., 2012), but for which regulations remain wanting (Foster and Garduño, 2013). This results in a lack of coordination and planning in the exploitation of this space, illustrated by conflicts over use (Bobylev, 2009).

In particular, the resilience of groundwater resources has become a major issue. On the one hand, 40% of the water distributed in the water supply networks of Europe comes from urban aquifers (Eiswirth et al., 2004), while on the other hand, geothermal energy is now considered as a strategic urban resource (Lund et al., 2011), (Herbert et al., 2013) since the European Council made a commitment to reduce greenhouse gas emissions by 20% by 2020 (European Commission, 2009). In parallel, underground structures involving impervious elements or pumping and re-injection devices, can impact groundwater flow (Attard et al., 2016c). Impervious structures can act as an obstacle to the flow (Epting et al., 2008), (Pujades et al., 2012). Draining structures can result in a fragmentation of urban flow systems (Attard et al., 2016b). In addition, underground structures can impact groundwater quality (Chae et al., 2008), (Attard et al., 2016a) and temperature (Hu et al., 2008), (Epting and Huggenberger, 2013), (Ferguson and Woodbury, 2004).

Regarding groundwater temperature, the heat island effect on groundwater due to urbanization has been clearly observed in many cities around the world (e.g. Zhu et al., 2010, Taniguchi et al., 2009, Menberg et al., 2013a). In particular, Menberg et al. (2013b and Benz et al. (2015) used an analytical heat flux model and a GIS approach to demonstrate that underground structures makes up a significant share of the total anthropogenic heat flux into urban aquifers. In addition to that, Ampofo et al. (2004) used a mathematical model written with an engineering equation solver to investigate the heat load of an underground railway. The authors showed that heat absorbed by the earth surrounding a subway can reach 30% of the total heat generated by the structure. Finally, Epting and Huggenberger (2013) used a deterministic modeling approach to assess the thermal potential natural state and the present state of the groundwater body of Basel (Switzerland). The heat-transport model showed a major influence of deep underground structures on groundwater temperature. On the one hand, the total anthropogenic heat flux of a city into groundwater provides a potentially sustainable geothermal resource (Benz et al., 2015). However, according to (Hähnlein et al., 2013) the shallow geothermal system is only sustainable if the generated energy is mainly renewable energy. Consequently, the total anthropogenic heat flux should be quantified (Benz et al., 2015) and extracted in areas where groundwater temperatures are high (Allen et al., 2003, Revesz et al., 2016). On the other hand, groundwater cooling systems can be disturbed where temperatures are increased by anthropogenic heat flux Epting et al. (2013).

Understanding the thermally affected zone (TAZ) of both urban underground structures and groundwater heat pump systems (GWHPS) is important as it could facilitate the management of urban underground development and geothermal exploitation. Since the TAZ of GWHPS has been described thoroughly in previous works (Lo Russo et al., 2012), (Lo Russo et al., 2014), (Sciacovelli et al., 2014), the aim of this paper is to quantify the TAZ of two common underground structures on urban groundwater temperature: (1) impervious deep foundations, and (2) a structure with a drainage and re-injection system. In addition, the cumulative impact of these structures was assessed at the scale of the city of Lyon (France). The consequences on the geothermal potential of urban aquifers are discussed regarding the TAZ and the heat flow generated by underground structures.

2. Study site

The area of the city of Lyon (France) (GPS coordinates: $45.75^{\circ} N/4.85^{\circ} E$) was chosen to study the impact of underground structures on groundwater temperature. This city has a great potential for urban underground development in the light of the criteria proposed in (Li et al., 2013b) (i.e. subsurface geotechnical quality, groundwater quality, geothermal energy, geomaterial quality, urban population, population density and GDP per capita). In practice, this potential is reflected by the economic attractiveness of Lyon (Carpenter and Verhage, 2014) at the European scale.

East Lyon is situated in a filled area of the Rhône Valley that collapsed during the Tertiary period (Fig. 1). During the Quaternary period, the successive advances and retreats of the Rhône glacier from the Lyon outwash lobe during different glaciations led to the deposit of materials of glacial origin (moraines, glaciofluvial sediments, loess) on the molasse dating from the Miocene period (Mandier, 1984). The relief stemming from Quaternary origins is marked in particular by radial morainic hills between which the melt waters of the last glacial maximum produced glaciofluvial corridors (Franc, 2005), (Mandier, 1984). The modern fluvial deposit of the urban area is approximately 20 m thick with a hydraulic conductivity of $1 \cdot 10^{-3}\ \mathrm{m} \cdot \mathrm{s}^{-1}$ (Nicolas et al., 2004). The modern fluvial deposit overlies the molasse layer which is approximately 150 m thick with a hydraulic conductivity of $1 \cdot 10^{-5}\ \mathrm{m} \cdot \mathrm{s}^{-1}$ (Nicolas et al., 2004). In the more densely populated districts of the area studied, the groundwater table is 5 m below the surface. The alluvial aquifer is recharged upstream by groundwater flow from two eastern glaciofluvial corridors and on the upper surface by infiltration and network leakages (i.e. water supply and sewage). The average groundwater temperature in the urban area is approximately 15 °C (Chartier et al., 2009).

The groundwater regime of the Lyon city area has already been investigated to assess the cumulative impact of underground structures on groundwater flow (Attard et al., 2016b). The main direction of the regional groundwater flow is illustrated in Fig. 1. The hydraulic gradient is approximately 0.2%. In this hydrodynamic context, two common design techniques can be proposed to build underground structures. These design techniques consist in (1) ballasting the underground structure in order to resist hydrostatic pressure, or (2) draining the groundwater under the structure in order to remove the hydrostatic pressure. In the following, the former design techniques were associated with an impervious structure and the latter with a draining structure.

3. Methodology

3.1. Individual impacts of impervious and draining structures

First, the impacts of two design techniques, (1) an impervious structure and (2) a draining structure, on groundwater temperature were simulated in a generic 1 km^2 bi-layered aquifer with hydraulic and material properties similar to that of the Lyon urban aquifer. This generic case was assumed to reproduce an urban aquifer recharged by precipitations and network losses, and discharging into a river downstream. As described in (Youngs, 1990) in form of analytical results, this configuration leads to a horizontal groundwater flow. To assess the long term influence of these underground structures on groundwater temperature, two scenarios were computed with a 20-year simulation. Table 1 and Fig. 2 summarize the geometric setup, the parameterization, the natural and anthropogenic model boundaries, for flow and thermal transport of the scenarios 1 and 2. The impervious structure, 50 m wide, 100 m long and 15 m deep, was considered without anchored foundations. The enclosure of this structure is 1 m wide. The draining structure, was considered with anchored foundations 25 m deep and 1 m wide. In addition, it was considered with a drainage slope at its base (i.e. in the plane $Z = -15$ m), and with 8 re-injection wells 25 m away from the upstream diaphragm wall. In both cases (i.e. the impervious structure and the

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