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Urban groundwater age modeling under unconfined condition – Impact of underground structures on groundwater age: Evidence of a piston effect

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SUMMARY

In this paper, underground structures are shown to have a major influence on the groundwater mean age distribution described as a *dispersive piston effect*. Urban underground development does not occur without impacts on subsoil resources. In particular, groundwater resources can be vulnerable and generate disturbances when this space is exploited. Groundwater age spatial distribution data are fundamental for resource management as it can provide operational sustainability indicators. However, the application of groundwater age modeling is neglected regarding the potential effect of underground structures in urban areas. A three dimensional modeling approach was conducted to quantify the impact of two underground structures: (1) an impervious structure and (2) a draining structure. Both structures are shown to cause significant mixing processes occurring between shallow and deeper aquifers. The design technique used for draining structures is shown to have the greatest impact, generating a decrease in mean age of more than 80% under the structure. Groundwater age modeling is shown to be relevant for highlighting the role played by underground structures in advective–dispersive flows in urban 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% (Un-Habitat, 2008) from now to 2050. Despite this anthropic pressure, the protection of natural spaces remains a major challenge in the effort to limit horizontal urban sprawl. The influence of these two constraints, anthropic pressure and property economics, leads mechanically to the vertical development of urban areas, particularly due to the potential provided by the subsoil for urban growth. In parallel, the urban subsoil is now recognized as a space rich in resources: available water, available space, geomaterials and geothermal heat (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), detrimental to the different systems of the underground environment.

In particular, the resilience of groundwater resources appears to be a major issue. Although 40% of the water distributed in the water supply networks of Europe comes from urban aquifers (Eiswirth et al., 2004), urban densification is leading to the construction of ever-deeper structures (Bobylev, 2009): subways, building foundations, underground carparks, etc., that interact with this resource. The interaction between groundwater and these structures can generate risks and disturbances. The flow rates drained by underground structures can impact on groundwater quality (Chae et al., 2008). The flow rates drained generate piezometric depressions giving rise to compactions (Modoni et al., 2013). On the contrary, damage to buildings can be caused by rises in groundwater levels, resulting in the flooding of lower levels, excessive hydrostatic stress exerted on buildings, and the corrosion of foundations (Lerner and Barrett, 1996). In addition, the heat island effect on groundwater due to urbanization has been clearly observed in many cities around the world (Zhu et al., 2010; Taniguchi et al., 2009; Menberg et al., 2013). Considering geothermal heat as a strategic urban resource (Lund et al., 2011; Herbert et al., 2013), underground structures can significantly affect groundwater temperatures (Epting and Huggenberger, 2013).

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A recent review focused on the impact of underground structures on the flow of urban groundwater (Attard et al., 2016). Underground structures were shown to have two types of impact on groundwater flow. They can (1) impede the natural flow of the groundwater. This is the case when an impervious underground structure is built. They can also (2) disturb the groundwater budget of the flow system. This is the case when a draining underground structure is built. These disturbances can extend over an area exceeding the scale of the structure and the timescale can cover more than several decades. All the literature studied in this review dealt with the impact of underground structures on advective flow. However, up to now, the impact of underground structures on dispersive flow has not been covered by the scientific literature.

According to Kazemi et al. (2006), groundwater age modeling has been demonstrated as relevant for assessing the renewability of groundwater reservoirs, recharge rates, groundwater flow velocities, the identification of groundwater mixing processes, and the vulnerability of the resource to pollution. In particular, the reservoir theory on hydrodispersive systems was generalized and investigated (Cornaton, 2004; Cornaton and Perrochet, 2006a,b) and the computational efficiency of these works opened a range of new applications regarding the depiction of groundwater age distribution and residence time. Characterizing the influence of underground structures on groundwater age could allow understanding how they contribute to the evolution of the residence time of groundwater in urban areas, and the role they play in the dispersive spreading of pollutants. Finally, the influence of underground structures on groundwater age could provide complementary knowledge regarding the impact of underground structures on groundwater, which integrate dispersive processes in urban areas.

The aim of this paper is to present an application of the reservoir theory applied to hydrodispersive systems in order to assess the influence of underground structures on groundwater age distribution in urban aquifers. In particular, this paper will focus on the influence of two common underground structures, (1) impervious deep foundations, and (2) a structure with a drainage and reinjection system, on groundwater age under unconfined condition.

2. Materials and methods

2.1. Definitions, system description and computational domain

The *age* of water is the time that elapsed since it entered the system considered (Etcheverry and Perrochet, 2000). At the macroscopic scale, the age of a water sample is a probability density function. Thus, a mean value of the probability density function of groundwater age can be defined at any point in a flow system. This paper focuses on the influence of underground structures on the spatial distribution of the mean value of groundwater age.

Fig. 1 illustrates the conceptual problem of interest of this paper. According to Attard et al. (2016), several urban areas and underground structures are built on a multi-layered aquifer system. This is the case of Paris (France), Barcelona (Spain), Hong Kong (China), Lige (Belgium), and Turin (Italy). As illustrated in Fig. 1, this layering, often accompanied by high permeability contrasts, contributes to a vertical gradient of groundwater mean age; the deeper the groundwater, the older it is. In these hydrodynamic contexts, several design techniques can be proposed to build the underground compartment of a city. In particular the most common 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 first design techniques were associated with an impervious structure and the second with a draining structure.

The impact of these two design techniques on groundwater mean age distribution were simulated in a 2 km bi-layered aquifer. The first layer was 20 m thick and the second underlying layer was 130 m thick (see Fig. 2). In both cases (i.e. the impervious structure and the draining structure), the structure was located near the center of the area studied (i.e. $X = 1000$ m and $Y = 1000$ m) (see Figs. 3 and 4).

The impervious structure, 50 m wide and 100 m long and 15 m deep, is built without anchored foundations (see Fig. 3). The draining structure, 50 m wide and 100 m long and 15 m deep, is built with anchored foundations 25 m deep and 1 m wide. In addition, it was built 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 (see Fig. 4).

To assess the influence of the structure on the mean age distribution of groundwater, three scenarios were computed and compared: (1) a simulation of flow in the natural state (i.e. without underground structure), (2) a simulation with the impervious structure, and (3) a simulation with the draining structure. First, hydraulic head distributions are compared in a cross-section view $Y = 1000$ m. Secondly, the mean age distributions are compared and discussed.

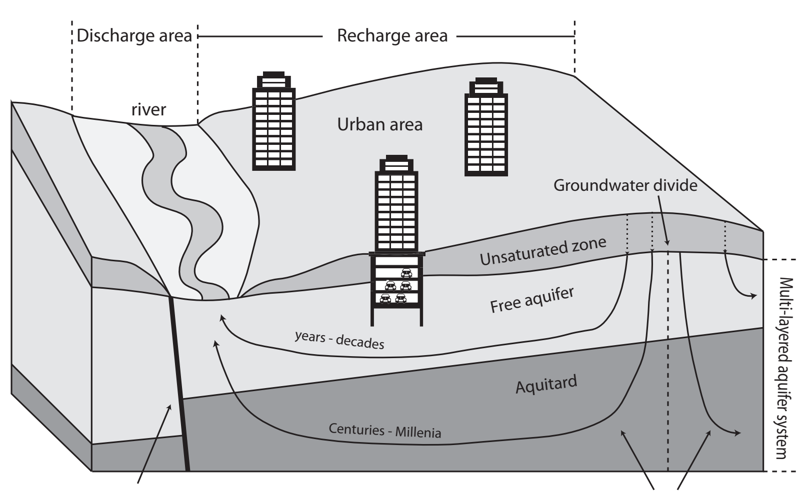

Fig. 1. Illustration of a regional hydrogeological system with the different possible flow paths from the recharge to the discharge areas (modified from Kazemi et al. (2006)).