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Quantification of groundwater recharge in urban environments

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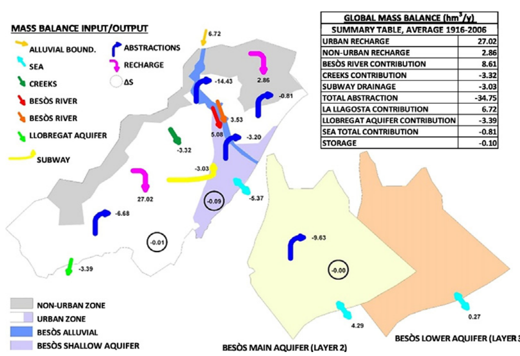
HIGHLIGHTS

- Groundwater management in urban areas requires adequate tools.
- A key difference in urban and natural areas lies in recharge evaluation.
- This methodology allows to quantify the recharge into aquifers in urban areas.
- Recharge calculations by defining and applying some analytical equations.
- Validation is assessed based on groundwater flow and solute transport modeling.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater management in urban areas requires a detailed knowledge of the hydrogeological system as well as the adequate tools for predicting the amount of groundwater and water quality evolution. In that context, a key difference between urban and natural areas lies in recharge evaluation. A large number of studies have been published since the 1990s that evaluate recharge in urban areas, with no specific methodology. Most of these methods show that there are generally higher rates of recharge in urban settings than in natural settings. Methods such as mixing ratios or groundwater modeling can be used to better estimate the relative importance of different sources of recharge and may prove to be a good tool for total recharge evaluation. However, accurate evaluation of this input is difficult. The objective is to present a methodology to help overcome those difficulties, and which will allow us to quantify the variability in space and time of the recharge into aquifers in urban areas. Recharge calculations have been initially performed by defining and applying some analytical equations, and validation has been assessed based on groundwater flow and solute transport modeling. This methodology is applicable to complex systems by considering temporal variability of all water sources. This allows managers of urban groundwater to evaluate the relative contribution of different recharge sources at a city scale by considering quantity and quality factors. The methodology is applied to the assessment of recharge sources in the Barcelona city aquifers.

1. Introduction

Groundwater is considered a key factor in the management of urban areas with increasing frequency (Lerner, 1996; Chilton, 1997, 1999;

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Eyles, 1997; Ellis, 1999; Howard and Israfilov, 2002; Custodio, 1997, 2004 and list of studies compiled by Naik et al., 2008). Some cities perform intensive pumping of groundwater for various uses (water supply, industry, etc.), which can produce a number of undesirable consequences such as ground subsidence (Pipia et al., 2013; Serrano-Juan et al., 2017) or deterioration of the quality of water as a result of various specific causes (e.g., seawater intrusion, Pool et al., 2015; Vázquez-Suñé et al., 2006). Moreover, the pumping of groundwater in many cities tends to be reduced or abandoned due to pollution and/or changes in land use (e.g., relocation of industries). In the latter case, the decline in groundwater extraction has caused a recovery of piezometric levels, generating floods and causing damage to underground infrastructure in many urban areas (García-Gil et al., 2015). Such is the case of Barcelona and its urban environment (Vázquez-Suñé et al., 2005).

To control these structural problems, it is usually necessary to pump groundwater in specific areas within the urban area (underground parking areas, building basements, tunnels, etc.). It is important to note that groundwater extraction may be necessary or useful to address various aspects of the growing demand for urban water. It is also due to become a strategic resource that can meet demand in moments when the usual supply sources may be encountering problems (drought, accidents, etc.). The latter consideration causes us to wonder whether urban groundwater can be used safely.

Urban aquifers can be impacted by very diverse pollution sources, which include recharging from the losses of sewerage, polluted urban runoff, polluted rivers or other surface water, seawater intrusion, etc. As a result, a large number and variety of contaminants can be found in urban aquifers (Howard et al., 1996; Barret et al., 1999; Pitt, 2001; Lerner, 2002; Morris et al., 2005; Vázquez-Suñé et al., 2005; Wakida and Lerner, 2005; Musolff, 2009; Ascott et al., 2016). In addition to "common" pollutants in the urban water environment, there are numerous organic pollutants of various origins, including a little understood and poorly legislated group known as emerging organic contaminants (EOCs), which are of particular concern for several reasons (Ellis, 2006; Tubau et al., 2010; Jurado et al., 2012a, 2012b, 2014; Petrie et al., 2015). To address these problems, we must understand the processes that determine the biological and chemical quality of urban groundwater, which in turn makes it necessary to quantify the groundwater balance and especially the recharge mechanisms (origin, quantity and quality).

Groundwater management in urban areas requires a detailed knowledge of the hydrogeological system as well as the adequate tools for predicting the amount of groundwater and water quality evolution. In this sense, experience in urban groundwater is much less than in natural areas. A key difference lies in recharge evaluation. A large number of studies have been published since the 1990s that evaluate recharge in urban areas (see list of studies compiled by Naik et al., 2008), with no specific methodology. However, it is established that new urban groundwater recharge sources appear within supply network losses and sewer losses. Furthermore, evapotranspiration decreases due to the sealing surfaces in urban areas. Therefore, there are generally higher rates of recharge in urban settings than in natural settings (Lerner, 2002; Vázquez-Suñé et al., 2005). Evaluation of the contribution of each recharge source has been addressed (Lerner, 2002). Given these uncertainties, mixing ratios can be used to better estimate the relative importance of different sources of recharge (Vázquez-Suñé et al., 2010; Tubau et al., 2014). Furthermore, groundwater modeling may prove to be a good tool for total recharge evaluation (Vázquez-Suñé and Sánchez-Vila, 1999; Yang et al., 1999; Lerner, 2002; Hussein and Schwartz, 2003; Dahan et al., 2004; Trowsdale and Lerner, 2003, 2007; Cox et al., 2007). However, this type of modeling requires a specific approach to identify the contribution of each particular source to the total recharge.

To address these specified uncertainties, a methodology is presented to perform groundwater modeling in urban areas that considers flow and solute transport. However, several issues have hindered the application of the methodology to real cases with numerous recharge sources, such as urban recharge. The first issue is associated with limited experience with the identification and selection of appropriate solutes. The second issue is the unavailability of extensive head and concentration records. Small and sparse records (in time and space) could cause the numerical solution to be non-identifiable or unstable.

The objective of this paper is to present a methodology to help overcome some of the issues discussed above. This methodology will allow us to quantify the variability in space and time of the recharge into aquifers in urban areas. In this case, the considered potential sources of recharge are: (1) direct rain and urban runoff infiltration, (2) losses from the sewer system, (3) losses from the water supply system, and (4) other specific sources of recharge (i.e., river infiltration, seawater intrusion, etc.). Recharge calculations have been initially performed by defining and applying some analytical equations, and validation has been assessed based on groundwater flow and solute transport modeling. This allows managers of urban groundwater to evaluate the relative contribution of different recharge sources using a flow and solute transport modeling approach at a city scale by considering quantity and quality factors. The methodology is applied to the assessment of recharge sources in the Barcelona city aquifers.

2. Methodology

The proposed method is applicable when groundwater data are sparse. This method can be considered a variation of the water table fluctuation mass balance method (Healy and Cook, 2002; De Vries and Simmers, 2002). In essence, it is based on calibrating a large-scale model while using appropriately parameterized areal recharge functions.

In practice, the method consists of the following steps: 1) Conceptual model definition, 2) Implementation into a numerical model, 3) Parameterization of areal recharge, 4) Calibration, and 5) Iteration. These steps are defined as follows:

2.1. Conceptual model definition

This is achieved using conventional hydrogeological methods. It requires understanding geology, hydrogeology, meteorology, hydrology, soil uses, pumping rates, hydrochemistry, etc. Emphasis must be placed on evaluating not only total inputs and outputs but also their evolution over time.

2.2. Implementation into a numerical model

Once a conceptual model has been defined, a numerical model is built. This requires specifying all parameters as well as the spatial and temporal discretization and boundary conditions (lateral inputs, recharge, pumping rates, etc.).

2.3. Parameterization of areal recharge

Urban recharge is defined as a prescribed recharge inflow as follows:

$$r(x,t) = \sum_{i=1}^{Nf} \beta_i f_{Ri}(x,t) \quad (1)$$

where r(x,t) is the recharge rate (here expressed per unit area and per unit time), Nf is the number of terms, β_i are unknown urban recharge parameters to be estimated later and $f_{Ri}(x,t)$ are functions representing the time variation of recharge. Ideally, these functions represent different modes of urban recharge. The fact that they are left in terms of unknown factors β_i should simplify their definition, which must be prescribed by the modeler. As discussed in the Introduction, a detailed account of all processes involved can be quite difficult. Factors affecting these processes may include: (1) recharge sources (rainfall, water