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Research article

Assessment of urbanization impact on groundwater resources in Hanoi, Vietnam

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ABSTRACT

In this study, the impact of urban development on groundwater resources of Hanoi City was assessed in terms of: (1) change of land use practice, and (2) increasing groundwater abstraction due to urban population growth. To this end, a coupled hydrological rainfall-runoff and groundwater flow simulation with WetSpa and MODFLOW codes was carried out with a set of spatial and temporal data of meteo-hydrology, land use, groundwater abstraction, population growth, and losses from the city water supply and sewerage system. The results of the simulation indicate that infiltration from rainfall contributes with 53.6% to the recharge of the groundwater system in Hanoi City, followed by seepage from rivers and lakes (31%). The remaining 15.4% was attributed to leakage from the municipal water supply and sewerage networks. This study also suggests that the main cause of groundwater level's decline in the city is the extensive groundwater abstraction, while an increase of the urban impervious areas due to urbanization only causes a slight decrease of groundwater recharge.

1. Introduction

In many cities in the world, urbanization changes the land use practice, usually by reducing the natural land area and increasing the impervious cover area (Murakami et al., 2005; Xu et al., 2007; Batisani and Yarnal, 2009; Mohan et al., 2011; Hassan and Nazem, 2016). The urban hard surfaces such as rooftops, driveways, streets, swimming pools, and patios don't allow water to penetrate the soil. In addition, streets act as streams, collecting storm water and channeling it into waterways. This leads to the decrease in the volume of rainfall that infiltrates through the ground and the resulting increase in the volume of surface water (Foster et al., 1993; Garcia-Fresca and Sharp, 2005; Mao and Cherkauer, 2009; Sajikumar and Remya, 2015). However, the reduction of direct infiltration can be counterbalanced by the reduction in evapotranspiration, and new sources of recharge may arise in the urban environment, such as losses in the sewerage system or in the water distribution system (Kim et al., 2001; Wolf et al., 2004; Blackwood et al., 2005).

On the other hand, the increase of groundwater abstraction to meet the water supply demand of a growing urban population growth is one of the causes of groundwater depletion in megacities (Lerner and Barrett, 1996; Foster et al., 1998; Hoque et al., 2007; Mpamba and Hussen, 2008; Naik and Tambe, 2008). This decline of groundwater level can lead to an increase of the groundwater recharge rate as the deep percolation depends on the characteristics of the unsaturated zone, mainly the hydraulic conductivity, root depth, water content of the soil, and the gradient of hydraulic potential between the unsaturated and saturated zone (Bouwer, 1978; Hillel, 1982).

Thus, the impact of urbanization on groundwater resources can be assessed by evaluating the two most important variables: recharge rate and groundwater level. However, evaluating the impact of recharge on groundwater resources in an urban environment is different from evaluating the impact on natural systems for three reasons: (1) recharge sources are radically different; (2) lack of detailed information on the sewerage system and water distribution system as well as the position, duration and volume of water leaked from these systems; and (3) reduction of recharge and decline of groundwater level due to urbanization are inter-related as mentioned above, which cannot be independently quantified by a single simulation. Several methods have been developed to distinguish sources and to quantify the recharge rate of an urban groundwater system based on hydro-geochemistry and isotope tracer analysis of groundwater water samples (Kim et al., 2001; Choi et al., 2005; Morris et al., 2006; Vázquez-Suñé et al., 2010). In essence, these methods only provide a "snapshot" of recharge around the time of the sampling; thus they are not suitable for assessing the impact of the urbanization process on the variation of groundwater recharge and resources. In addition, these methods do not show the impact of increasing impervious cover area and declining groundwater

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level to groundwater recharge during the urban development. A comprehensive evaluation of all recharge sources can be achieved through flow and transport simulation when previous data on groundwater head and quality are available (Yang et al., 1999; Vázquez-Suñé and Sánchez-Vila, 1999; Trowsdale and Lerner, 2007).

A recent study demonstrated that the main contributors to total recharge of Barcelona city aquifers are: rainfall, surface runoff and water bodies (48%), followed by losses from the sewerage network (30%), and losses from the water supply network (22%) (Vázquez-Suñé et al., 2010). For tropical cities where annual precipitation is 2.5–4.5 times higher than in Barcelona, contribution from rainfall and the resulting overland flow and surface runoff to total recharge can be foreseen as a major portion. As land use change is one of the factors influencing the distribution and contribution of overland flow and surface runoff to ground water recharge, land use maps at different time periods can be used as a variable to assess the impact of urbanization process to the groundwater resource.

Hanoi is considered the second most rapidly developing city in Vietnam in the last two decades. Also in this period, the Quaternary aquifers, the most important source for the city water supply are reported as being degraded: the annual lowering of groundwater level 0.3–0.5 m causes land subsidence of up to 41 mm/year, additionally, the aquifer are exposed to saltwater intrusion from southeast (On, 2012). The report raised the two main causes for the degradation: reduction of groundwater recharges and increase of groundwater abstraction. This research analyses the impact of urbanization development to groundwater resources of Hanoi City, based on land use change and groundwater abstraction. Using these variables as input, a coupled hydrological-groundwater flow modeling is used to simulate the temporal changes of groundwater recharge and level. Based on this simulated result, a detailed analysis of the relationship between rainfall, river discharge, components of recharge, and groundwater level is carried out to reveal the factors that have the most significant influence on the groundwater resources in the study area. This study provides insights into the impact of urbanization on groundwater budget in developing cities where groundwater is the main source for urban water supply.

2. Site description

2.1. Hanoi's hydrogeology

Hanoi, the second largest city in Vietnam with a current area of about 3300 km^2 and 7.6 million of inhabitants, is located at the heart of the Red River Delta plain (Fig. 1). Three quarters of the city's area is of flat terrain gradually steeping down in the North-South and West-East directions with an averaged elevation 5–20 m above mean sea level (AMSL). The remaining area is covered by hills and mountains with an elevation of 50–750 m AMSL located in the West and North-West (Fig. 1). Flowing through Hanoi city, the Red River is the second largest in Vietnam with a mean flowrate of 1054 and 4228 m^3/s for dry and rainy season respectively. The mean annual precipitation in Hanoi City is about 1760 mm, out of which 78% falls in the hot rainy season from May till October and the remaining 22% falls in the cool dry season from November till April every year.

Hydrogeologically, the groundwater of Hanoi City resides in porous media of Quaternary formations distributed in the flat terrain and in fault/fracture zones of pre-quaternary hard rock formations exposed on the hills and mountains. The Quaternary formations are stratigraphically divided into two aquifers intercalated with two aquitards from top to down as follows: (1) the upper aquitard (*UA*), with averaged thickness of 18.5 m and hydraulic conductivity 0.05 m/day, exposes on the ground surface in the southern area of Hanoi; (2) the Holocene aquifer (*QH*), with average thickness of 18.9 m and hydraulic conductivity 12.5 m/day, underlies directly the *UA* and outcrops mainly in the North and as narrow bands along rivers; (3) the lower aquitard (*LA*), with average thickness of 16.5 m and hydraulic conductivity 0.02 m/day, is completely covered by the *UA* and *QH* formations; and (4) the Pleistocene aquifer (*QP*), of average thickness 59.5 m and hydraulic conductivity 31.9 m/day, overlays directly on the partly weathered or denuded surface of the hard rock formations. More information on the lithology, thickness and hydraulic conductivity of these aquitards and aquifers is provided in Table 1.

A three-dimensional representation of the hydrogeological stratigraphy for Hanoi City built on the basis of 238 stratigraphic well-logs is shown in Fig. 2. This diagram shows the existence of many "vertical hydrogeological windows" where the *LA* aquitard is absent and the *QH* and *QP* aquifers are interconnected. The *QH* aquifer is recharged from rainfall and surface water percolating vertically through the *UA* aquitard or with river water in the southern part of Hanoi, where the Red River system cuts into the aquifer. The QP aquifer is only replenished with rain and surface water in the Northern and Western part of Hanoi City where it outcrops. Based on the pumping tests conducted by Quyen (2016), the *QP* aquifer has been estimated to receive water discharging from weathered and fractured zones at the rate of approximately 2.76 l/s/km along the Western contact margin. At the bottom, this aquifer is lined with layers of siltstone, shale and schist of hard rock formations, and therefore, it was assumed there is no flow through this layer.

2.2. The development of Hanoi City

The development of Hanoi City started in the 11th century as the capital of Vietnam, and before the year 1975 remained in the style of a town with no high-rise buildings. Only when the country's economy burst into bloom in the last decade of the 20th century has Hanoi was growing rapidly to become a modern crowded city with an urban population increasing from 1.44 million in 1990 to 3.41 million in 2015 (Table 2). A sudden development in city's infrastructure accompanied this growth, meaning urbanized land with new roads and buildings replaced agricultural and natural (A&N) land; more sewerage and water supply networks were constructed; and many small lakes and ponds were partly or fully filled up with soil to be transformed into resident areas or industrial parks (Table 2).

2.3. Water supply and wastewater generation in Hanoi City

Since the beginning of the nineteenth century, groundwater has been the principal water supply source for Hanoi City. Before 1990s, a volume of about 350,000 m^3/day of groundwater was exploited from the *QP* aquifer and about 200,000 m^3/day from the *QH* aquifer. Water supply for the urban area consist of mainly deep large diameter wells drilled in the QP aquifer over 16 well fields and an underground distribution system hundreds kilometers in length. By 2010, the groundwater abstraction volume increased to about 950,000 m^3/day from the *QP* aquifer and 350,000 m^3/day from the *QH* aquifer. This increased in the abstraction caused a declined rate of the groundwater levels of 0.5–0.8 m/year for the *QP* aquifer during the period 1990–2010. The groundwater level decline stopped after 2010 when a volume of 250,000–350,000 m^3/day from a surface water treatment plant located 80 km upstream of the Red River was added to meet the increasing demand of newly built residential areas and industrial parks.

Concomitant with urban population growth, the sewerage and water networks in the urban area have been also expanded and upgraded. However, leakage and losses from these systems are still considerable. By comparing the water volume produced by water treatment plants and the volume gauged at the water meter of consumers, it was estimated that the losses through the distribution system were about 36% (in 1990s) to 27% (in 2010s) (VWSA, 2015). The leakage from the urban sewerage system was also estimated at 25% (in 1990s) and 21% (in 2010s) by subtracting the sewage volume gauged at the urban outlet from the total water supply volume gauged at consumer's water meters. It was noticed that the calculated leakage value may underestimate the