Sustainability Assessment of Groundwater Abstraction in Hanoi, Vietnam

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1. INTRODUCTION

The appropriate term of sustainability has been considered as a process that "*meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). This concept has nowadays become one of the global critical issues for all application fields. Specifically, '*groundwater sustainability*' may refer to the way of development and use of groundwater resource, in which the resource can be preserved for an indefinite time without causing any adverse eco-environmental and social consequences (Alley *et al,* 1999).

Groundwater plays a key role in public water supplies around the world. Worldwide, more than two billion people depend on groundwater for their daily supply and over half of the world's population depends on groundwater for drinking water (Anthony, 2006). The excessive groundwater abstraction has caused serious groundwater-level declines in a number of areas (Shamsudduha *et al*, 2009). Declining groundwater levels have caused a number of adverse impacts on the environment condition such as groundwater depletion, which practically threatens sustainable aquifers (Akther *et al*, 2009), land subsidence resulting from compaction of aquifer materials (Konikow & Kendy, 2005) and groundwater pollution due to additional recharge from wastewater sources (Hoque *et al*, 2007). Since the amount of groundwater abstraction has been rapidly and continuously increasing worldwide, achieving sustainable management of groundwater resources is one of the essential objectives for the future of countries (Mende *et al*, 2007). The annual cycle in groundwater levels associates with those in rainfall and river water levels, but long-term trends results from increasing groundwater withdrawal (Bui *et al*, 2012a).

The Vietnamese capital, Hanoi, is the target area addressing the sustainability issue of groundwater abstraction because: (i) the groundwater abstraction has been rapidly and continuously increasing and the demand for clean water is becoming rather urgent; (ii) the water supply significantly depends on this valuable resources (up to almost 100%) for three main purposes such as irrigation, domestic, and industrial uses; and (iii) the rapid exploitation of the groundwater without an appropriate management system has reportedly caused a series of adverse impacts such as drying up of shallow wells, decline of groundwater level locally and seriously, and land subsidence (Bui *et al*, 2012a; Tong, 2008).

In order to obtain fundamental findings for further groundwater analyses required to ensure sustainable groundwater development of Hanoi, this study firstly (i) tests the applicability of a number of groundwater sustainability indicators suggested by the UNESCO/IAEA/IAH Working Group on Groundwater Indicators (Vrba & Lipponen, 2007), properly associated with currently available data; (ii) secondly assesses sustainability stage of groundwater abstraction; and finally (iii) provides useful suggestions for Hanoi groundwater sustainable development management. The selected indicators allow for assessment of groundwater sufficiency in proportion to population and water use, and its indications of groundwater depletion and vulnerability by assessing the proportion of groundwater abstraction to the estimated recharge and the exploitable groundwater resources. The research is fundamental for further sustainability assessment of groundwater resources in Hanoi.

2. STUDY AREA

Figure 1 shows the location of current Hanoi and distribution of the groundwater observation wells in the former area. Hanoi is located in the north-eastern part of Vietnam with the area of 3324.5 km^2. The population of more than 7 million (in 2014) accounts for 7.5 % of Vietnam in total (General Statistic Office of Vietnam). Hanoi belongs to the tropical monsoonal area with two distinctive seasons in the year, the rainy season from May to October and the dry season from November to April of the following year. The annual average rainfall is about 1,600 mm, the average humidity is about 80%, and the average temperature is around 24.3^{o}C. Evaporation is quite high with an annual average of 933 mm (Tong, 2008). The surface water system is recently polluted by organic compounds, in which, the lakes especially in this study area are significantly polluted (Tong, 2008). That is the main reason why the groundwater resources have become main water supply for the local inhabitants.

In our previous study, Bui *et al* (2012b), the authors comprehensively analysis of the aquifer system for potential groundwater resources in Hanoi. Hanoi's groundwater resources mainly exist in the topmost Holocene unconfined aquifer (HUA) and the shallow Pleistocene confined aquifer (PCA), while cleft and karst water exists in the Neogene water bearing layer and the Mesozoic fractured zones. In HUA layer, silty clay and various kinds of sands mixed with gravels are the main components. The HUA thickness is variously distributed, more than 35 m with an average of 15 m, approximately. The transmissivity and the specific yield of this layer ranges from 20 to 1,788 m^2/day and from 0.01 to 0.17, respectively. The HUA, thus, is distributed at a rate of about 55% in the south of the city area, and has a relatively high potential of groundwater resources, sufficient for the small to medium scale domestic water supply. The shallow Pleistocene confined aquifer (PCA) depth is also widely distributed, less than 10m in the North of the Soc Son District, around 20m in Dong Anh District, and up to 40 m in the South of the Red River. The PCA layers have a complex components of sand mixed with cobbles and pebbles. Moreover, the PCA thickness is variously changed, with the highest value of up to 50m and the average of 35 m approximately and trend increasing from the North to the South. With a large range of transmissivity from 700 to 2,900 m^2/day, and the specific storativity from 0.00004 to 0.066, PCA is the highest potential of groundwater resources and widely distributed at a rate of about 80% in the south of the city, serving the most important aquifer for the area water supply.

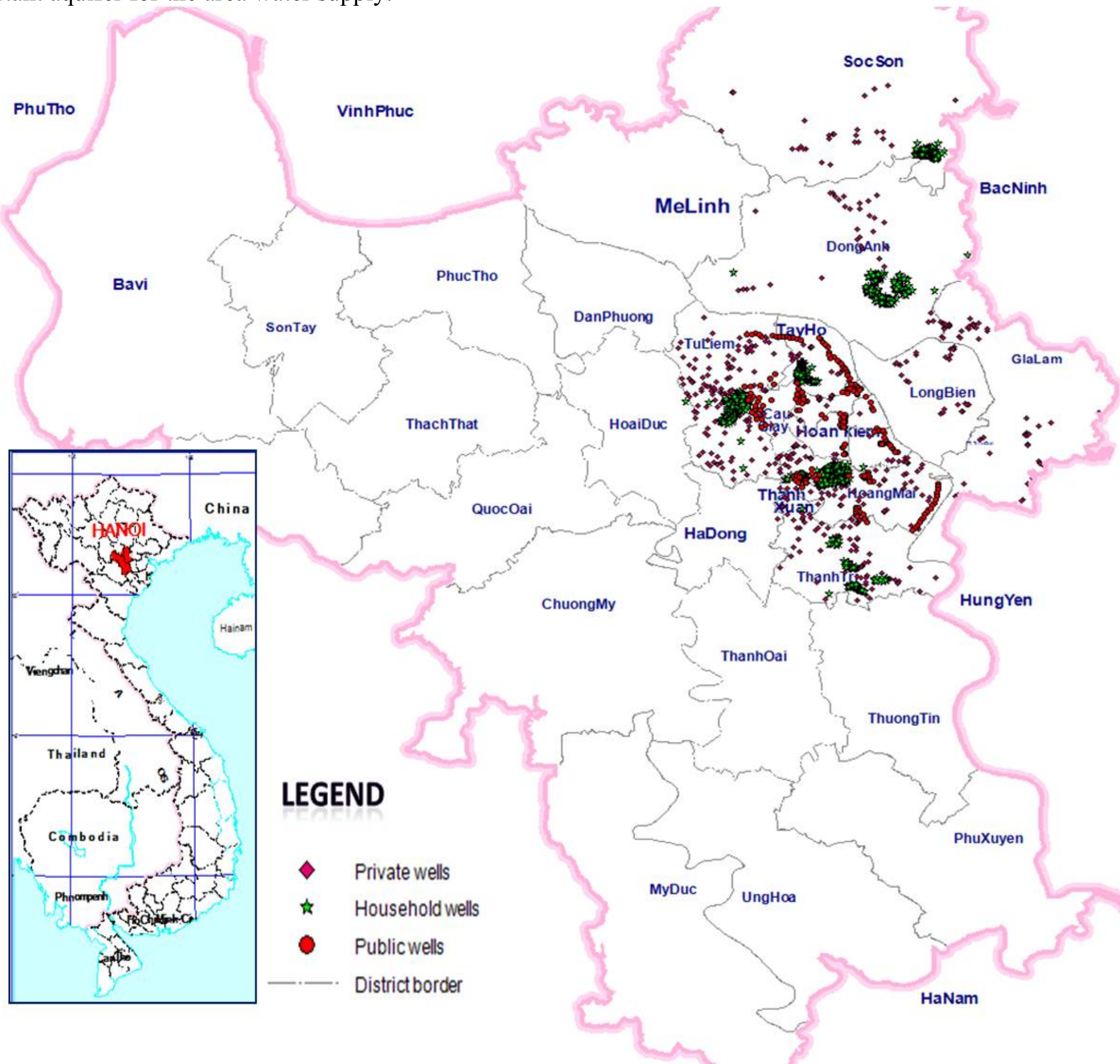

Figure 1 The study area and distribution of groundwater observation wells

3. DATA AND METHODS

Data sets of Ministry of Natural Resources and Environment (MONRE) are principally used to test the indicators. Variables needed for determining the indicators are presented in Table 1. Definitions and instructions for the calculation of the indicators have been provided by the Working Group on Groundwater Indicators (Vrba & Lipponen, 2007)

Table 1 Groundwater abstraction indicators, their formula, the variables used and the results

	Indicator GSI1	Indicator GSI2	Indicator GSI3
Indicator	Groundwater renewable resources per inhabitant	Total abstraction of groundwater per groundwater recharge	Total abstraction of groundwater per Exploitable groundwater resources
Formula	(Groundwater renewable resources)/Inhabitants	(Total abstraction of groundwater) ×100%/ (Groundwater recharge)	(Total abstraction of groundwater) × 100% / (Exploitable groundwater resources)
Unit	(m^3.year^{-1})/inhabitant	%	%
Variables used (Values)	• Recharge estimation: 276 mm/year (equal to 917,562,000 m^3/year) • Base flow and inflow: negligible (0) • Seepage: 230,954,511 (m^3/year) • Artificial recharge: negligible (0) • Surface area: 3324.5 (km^2) • Population: 7,095,900 inhabitants (in 2014)	• Groundwater abstraction by public wells: 977,600 m^3/day; by private wells: 88,946 m^3/day and by household wells: 733,016 m^3/day. • Recharge estimation: 276 mm/year (equal to 917,562,000 m^3/year) • Surface area: 3324.5 (km^2)	• Groundwater abstraction by public wells: 977,600 m^3/day; by private wells: 88,946 m^3/day and by household wells: 733,016 m^3/day. • Groundwater exploitable resources: 6,199,140 m^3/day
Results	162 m^3year^{-1}/inhabitant	71.6%	29%
Scale	Regional	Regional	Regional

4. INDICATOR APPLICATION

4.1. Groundwater Recharge, Exploitable and Abstraction in Hanoi

- The term "*recharge*" has been defined as "*as the downward flow of water reaching the water table, adding to groundwater storage*" in the book of "*Estimating Groundwater Recharge*" (Richard, 2010). The author mentions that the definition does not include water flow to an aquifer from adjoining groundwater system such as water movement from an unconfined aquifer to an underlying aquifer. This paper, thus, considers the recharge to Hanoi groundwater resource is the same as recharge to the HUA from precipitation. As shown on our previous study, Bui *et al* (2016), based on the data from national water resource monitoring and investigation projects of National Center of Water Recourses Planning and Investigation in period of (1995-2014), the recharge amounts is various from region to region with the minimum of 85 mm/year (at monitoring no.Q65 in Hoang Mai District in 2014) and the maximum of 1,028.52 mm/year (at monitoring no.Q67 in Tay Ho District in 2010). The average recharge estimation for Hanoi is about 276 mm/year.

Average groundwater recharge:

$$276 \text{ mm/year} \times 10^{-6} \text{ km/mm} \times 3324.5\text{km}^2 \approx 917{,}562 \times 10^{-6} \text{ (km}^3\text{/year)} = 917{,}562{,}000 \text{ m}^3\text{/year}$$

- The term "*exploitable*" means the amount of water that can be annually abstracted from a given aquifer under current socio-economic constraints, political priorities and ecological conditions. The latest estimation is carried out by The National Center of Water Recourses Planning and Investigation in 2015.

The amount of 6,199,140 m^3/day, combines natural dynamic storage, elastic static storage, a part of gravitational static storage, and the entrained storage, as the following formula:

$$Q_{kt} = Q_{tn} + (V_{dh} + \alpha V_{tl})/t + Q_{ct} \quad (1)$$

where:

Q_{kt}: the exploitable groundwater resources, m^3/day; Q_{tn}: the natural dynamic storage, m^3/day; V_{dh}: the elastic static storage, m^3; V_{tl}: the gravitational static storage, m^3; Q_{ct}: the entrained storage, m^3; α: the coefficient associating with natural and gravity static storage, %; t: exploitation time, 27 years (10^4 days) as usual.

- Total groundwater abstraction means the total withdrawal of water from a given groundwater body by means of wells, boreholes, springs and other ways for the purpose of public water supply and agricultural, industrial and other usage. In our previous study, Bui *et al* (2016), the total groundwater abstraction for different uses such as agricultural, industrial and domestic uses, have been reported by Scientific Research No.TNMT.02.33 of MONRE. Hanoi groundwater abstraction mainly includes (i) public exploitation wells managed by 25 Clean Water Supply Companies, (ii) private wells managed by approximately 47 schools, institutes, factories, small industries, communities, and so on, and (iii) 793,657 household wells. The sub-total groundwater abstraction estimations of group (i), (ii), and (iii) are 977,600 m^3/day, 88,946 m^3/day, and 733,016 m^3/day, respectively. Total groundwater abstraction is:

$$977{,}600 + 88{,}946 + 733{,}016 = 1{,}799{,}562 \ (m^3/day)$$

4.2. Calculation of Groundwater Sustainability Indicators (GSI) in Hanoi

4.2.1. Calculation of GSI1 Indicator

GSI1 used to estimate how much groundwater is theoretically available for each resident within one year. The groundwater renewable resources are calculated by the arithmetic sum of series components, such as the recharge from precipitation (recharge), the amount of surface water that infiltrates into groundwater (seepage), the amount of groundwater that discharges to surface water (base flow), the amount of groundwater recharged (discharged) from (to) the aquifers of the adjacent countries (inflow/outflow) and the artificial recharge (Vrba & Lipponen, 2007). This study investigates the sustainability assessment of groundwater abstraction at regional scale; the inflow/outflow is not considered in the following groundwater water balance equation.

$$\text{Groundwater renewable resources} = \text{Recharge} + \text{Seepage} - \text{Base flow} + \text{Artificial recharge} \quad (2)$$

Seepage:

Seepage values are various from areas to areas in Hanoi Capital. At Thuong Cat, Cao dinh, the values is about 194 ml/m^2.day, about 347ml/m^2.day at Luong Yen, Yen Phu; and 30ml/m^2.day at Thanhtri (Pham, *et al*, 2014). Thus the average number could be considered as the estimated seepage per meter square for Hanoi:

$$\text{Seepage per } m^2 = (194\ ml/m^2.day + 347ml/m^2.day + 30ml/m^2.day)/3 = 190.33\ (ml/m^2.day)$$

$$\text{Seepage} = 190.33ml/m^2.day \times 10^{-6}m^3/ml \times 3324.5 \times 10^6 m^2 = 632{,}763.17(m^3/day)$$

$$= 632{,}763.17 \times 365(m^3/year) = 230{,}954{,}511(m^3/year)$$

Artificial recharge:

Based on the Project Report of Plans to Improve Groundwater Resources Management and Protection Efficiency in Hanoi City (2014-2020), NAWAPI and BGR (2014), there have been several research projects regarding to scientific and technical backgrounds and proposed methods of artificial recharges for groundwater resources of Vietnam so far. These projects, however, have been lack of the experimental works for the proposed approaches. Thus the results have been practically limited in application. The amount of artificial recharge in this study is considered as negligible.

Base-flow:

On the one hand, in Nguyen *et al* (2012), the ground flow model (MODFLOW) coupled with the river flow routing model (MIKE 11) was utilized in order to explore the dynamic interactions between the surface water of the Red River in Hanoi and the groundwater of the adjacent alluvial aquifers. As for the results, upper part of the Red River in Hanoi exhibited flow interchange between aquifer and river, while the lower part of the river discharged into groundwater during the most parts of the year. On the other hand, in our previous study, Bui *et al* (2011), the average discharge of the Red River at the Hanoi station is 385 m^3/s in the dry season and 14,800 m^3/s in the rainy season. Therefore, base-flow, the amount groundwater that inflow to rivers becoming parts of surface water resources in Hanoi is basically considered as zero in this study.

Inhabitants of Hanoi Capital:

According to General Statistics Offices, Hanoi population is about 7,095,900 persons in 2014.

Groundwater Renewable Resources = Recharge – Baseflow + Seepage + Artificial Recharge

= 917,562,000 (m^3/year) - 0 + 230,958,556 (m^3/year) + 0 = 1,148,516,511 (m^3/year) ≈1.15 (km^3/year)

GSI1= (Groundwater renewable resources)/Inhabitants

= 1,148,516,511 (m^3/year) / 7,095,900 inhabitants = 162 ($m^3 year^{-1}$/inhabitant)

4.2.2. Calculation of GSI2 Indicator

Safe yield of a groundwater basin or aquifer system is defined as the amount of water that can be withdrawn from it without producing an undesired effect. GSI2 is percentage of the amounts of abstracted groundwater with respect to total groundwater recharge. GSI2 shows whether groundwater is used in a sustainable way or if there is any indication of over-exploitation. When abstraction is less than recharge, groundwater use is considered sustainable. Otherwise, when abstraction is more than recharge, groundwater use is considered non-sustainable.

GIS2= (Total abstraction of groundwater) ×100%/ (Groundwater recharge) (3)

= 1,799,562 (m^3/day) × 365 (day/year) ×100%/ 917,562,000(m^3/year) = 71.6%

4.2.3. Calculation of GSI3 Indicator

The term exploitable groundwater resource means the amount of water that can be annually abstracted from a given aquifer under current socio-economic constraints, political priorities and ecological conditions. The GSI3 indicator is the percentage of the abstracted groundwater amounts with respect to groundwater exploitable resources.

GIS3= (Total abstraction of groundwater) × 100% / (Exploitable groundwater resources) (4)

= 1,799,562 (m^3/day) ×100%/ 6,199,140 (m^3/day) = 29%

The results of the indicators GSI2 and GSI3 belong to one on the scenarios given an indication of the groundwater abstraction sustainability.

Scenarios 1: abstraction ≤ recharge/exploitable; i.e. < 90%

Scenarios 2: abstraction = recharge/exploitable; i.e. = 100%

Scenarios 3: abstraction ≥ recharge/exploitable; i.e. > 100%

5. DISCUSSION AND CONCLUSIONS

The indicators suggest that Hanoi groundwater is generally in a good shape. Groundwater is renewable and theoretically groundwater could be used on a larger scale and could be sufficient for normal uses. The quantity of groundwater renewable resource is not directly related to the amount of groundwater available for use. The renewable is the potential groundwater which is could be used probably under the certain constrains of the region and country. The ratio of total groundwater abstraction to groundwater recharge gives some indication of the low degree of development of groundwater resources in Hanoi. This means that the resource has been not practically utilized to provide a sufficient water use for local residents to meet the current demands and still has a potential in exploitation. However, in our previous study, Bui *et al* (2012b), the metropolitan area and the south parts (about 7% of the study area) are reported as over-exploitation, water table decline seriously occurred and even some parts are warning of land subsidence problems (Phi & Strokova, 2015). This indicates the limitation of the indicators and also the inappropriately distributed groundwater abstraction wells. Previously, Hanoi was small and the exploitation wells have been mainly located in the metropolitan areas. Recently, since 2008, Hanoi has extended and included Hatay and some parts of Vinhphuc and Hanam provinces. The previous area is about 15% of the current area. That is why even the serious groundwater decline occurred in the central area, the indicators show the general sustainability assessment for total extended area.

Therefore, to improve the sensitivity of the indicators which could be carried out in the smaller scales such as districts, metropolitan regions and so on, to make the better views for Hanoi's groundwater resources. The indicators could potentially support better for decision makers. In order to properly adapt the increasing water use demand of the industrialized and socialized Capital, the monitoring networks should be spatially and widely distributed all over the area, especially located along lake and riversides, to moderate the local over-exploitation problems and the environmentally adverse impacts, and enhance the natural recharge from these surface water systems to the aquifers. Improving a groundwater artificial recharge for the central is one of the effective ways to enhance the recharge for the aquifers and prevent groundwater degradation (Ngo, 2007). In general, the sustainability level groundwater abstraction in Hanoi is acceptable but locally unsustainable with serious declined water table. The research is fundamental for further sustainability assessment of groundwater resources in Hanoi.

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