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Research article

Groundwater sustainability assessment framework: A demonstration of environmental sustainability index for Hanoi, Vietnam

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ABSTRACT

There is mounting concern about how to support decision-makers in driving sustainable water resources management; science needs to support the decision-making process to promote evidence-based decisions. To this end, sustainability assessment is considered a useful technique, which provides enough information to assist management. This study proposed a groundwater sustainability assessment framework, which is developed from a regular sustainability assessment approach and analytical hierarchy process (AHP). In the proposed framework, the three main pillars (environmental, social, and economic) of the concept of sustainability were considered the three important sustainability criteria. Hence, we demonstrated the proposed framework for a Hanoi case study with focus on the environmental sustainability criterion. The concept of AHP was used to create the main sustainability components (the three criteria, associated with their aspects and indicators) of a hierarchy, which appropriately cover environmental sustainability issues of groundwater resources in the target area. Based on the available reliable data of the current problems in Hanoi, we proposed three main sustainability aspects (quantity, quality, and management) and, accordingly, selected their twelve environmental sustainability indicators. To determine a reasonable sustainability assessment, we considered a conventional linear and non-linear relationship between the indicators and the corresponding sustainability indices. As for the results from the Hanoi case study, the environmental sustainability indices obtained from using a combined linear and non-linear relationship case appropriately reflect the current situation, that is, the environmental sustainability assessment is close to reality. The sustainability indices of the quantity, quality, and management aspects of groundwater were appropriately assessed at acceptable levels, resulting in Hanoi being rated at the acceptable level in the final environmental sustainability index. The variability of the environmental sustainability indices indicated that the current groundwater abstraction networks are heavily concentrated in a few specific areas in Hanoi, which is not optimal for utilizing the rich natural recharge resources of the area. Improvement of the current poor groundwater quality and strict enforcement of environmental regulations are essential to enhancing the environmental sustainability and, more importantly, to drive Hanoi towards sustainable groundwater resources.

1. Introduction

The concept of sustainability has been considered 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

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application fields. The sustainability concept has been reviewed in the context of its three main pillars of environmental, economic, and social performances, in which environmental sustainability usually gains massive attention from scientists, governmental decision makers, and practitioners worldwide. The reason for this attention is probably that a sustainable environment could be considered a necessary prerequisite to a sustainable socio-economic system (Morelli, 2011). There has been great effort aimed at deriving an appropriate definition of environmental sustainability (Fulton et al., 2017; Liu, 2007; Moldan et al., 2012; Morelli, 2011; Sutton, 2004; World Bank, 2008; etc.). A fundamental way to express the environmental sustainability concept is that it is "the ability to maintain things or qualities that are valued in the natural and biological environments" (Sutton, 2004). Specifically, in water resources management, groundwater sustainability means enough quantity and quality of groundwater available at an acceptable price, which is available to meet social demands of the region without causing any environmental degradation (Plate, 1993). Groundwater plays a key role in water supplies worldwide and groundwater abstraction has been rapidly and continuously increasing (United Nations, 2015). There are a series of severe problems related to groundwater over-exploitation such as occurrences of groundwater decline, land subsidence, and groundwater pollution and health hazards (Gupta and Onta, 1997). Thus, achieving sustainable groundwater management from an environmental sustainability perspective for groundwater development is a challenge, and vital for sustainable development of countries.

It is apparent that science needs to support the decision-making process to promote evidence-based decisions. To this end, considering environmental sustainability of groundwater resources as a practical objective, the questions are how to translate this practical objective into a set of more specific actions, and how to provide decision-makers with enough information to assist management decisions to improve environmental sustainability. Regarding sustainability assessment methodologies, the Analytical Hierarchy Process (AHP) is a useful approach in dealing with multifaceted and unstructured sustainability problems (Boggia and Cortina, 2010; Yu, 2002). AHP has been successfully applied to various application fields and, for water resources specifically, it has been developed and utilized for specific sustainability problems of sustainable evaluation of water pollution (Si et al., 2010), regional water resources (Sun et al., 2016), and economic and social sustainability assessment of groundwater resources (Bui et al., 2017b, 2018). However, AHP has not been employed for an integrated sustainability assessment of groundwater resources in the literature, in which all three sustainability pillars (environmental, social, and economic) are considered in one sustainability framework. In such AHP sustainability assessment applications, appropriately defining the sustainability hierarchy components, including from the highest-level component of sustainability goals, the next level of the goal's features (criteria), the criterion's main characteristics (aspects), to the lowest level component (indicators), is one of the most difficult tasks. The criteria could be conceptually considered the three main sustainability pillars (Bui et al., 2017a). The aspects and indicators should be developed appropriately based on the current situations in target areas.

Regarding groundwater sustainability indicator development, UNESCO/IAEA/IAH Working Group first tried to define the groundwater sustainability indicators that follow the DPSIR (Driving forces, Pressures, State, Impacts, and societal Response) framework; most of these indicators focus on the environmental perspective directly (Vrba and Lipponen, 2007). Those indicators are basically related to the usual groundwater situation and can be used as a guideline for establishing sustainability indicators of any region worldwide. However, the Group has not mentioned how the increase of their indicator values positively or negatively affect one of the three specific sustainability pillars. Regarding groundwater quantity, for example, one indicator is defined as the ratio between groundwater abstraction and recharge. An increase of groundwater abstraction may be needed to meet cumulative social demand; this increase, however, eventually leads to a series of adverse environmental impacts like groundwater level decline, land subsidence, and even pollution. It is apparently difficult to judge whether the increase in indicator values contributes positively or negatively to one of the specific sustainability pillars. It is, therefore, necessary to develop a set of appropriate groundwater sustainability indicators from a particular pillar (environmental criterion in this case) to support the judgment clearly. The groundwater sustainability indicators (GSIs) should be selected according to the current environmental problems of the target groundwater resources and should be appropriately defined.

Dealing with the abovementioned research gaps, this study (i) proposes an AHP-based sustainability assessment framework for groundwater resources (AHP-SAG), and (ii) appropriately defines a set of sustainability hierarchy components (sustainability goal, aspects, and GSIs) for a case study of Hanoi, Vietnam to demonstrate the AHP-SAG framework from an environmental viewpoint. Based on the AHP context, the first level of the hierarchy is the final groundwater sustainability goal. This goal is reviewed for its three main criteria associated with the criterion's feature aspects, and, finally, these aspects are composed of the specific GSIs. GSIs provide a necessary foundation for sustainability in particular, and for the integrated sustainability assessment of groundwater resources in general in the target area.

2. Study area

2.1. Basic conditions of Hanoi

In Vietnam, groundwater has become the most important water supply source, especially in the fast-urbanizing capital, Hanoi, accounting for almost 100% of domestic water use for the communities (Bui et al., 2011). The geographical location and the main rivers and lakes of Hanoi are displayed in Fig. 1. For detailed information of the basic conditions of Hanoi, see Bui et al. (2018).

2.2. Current environmental sustainability issues with Hanoi groundwater resource development

According to our previous study (Bui et al., 2012a) regarding groundwater quantity, Hanoi groundwater resources exist mainly in the topmost Holocene unconfined aquifer (HUA) and the Pleistocene confined aquifer (PCA). The HUA, with its distribution area of 1499 km^2, accounts for a relatively high groundwater potential, sufficient for the small-to-medium-scale domestic water supply. PCA, with its distribution area of 3703 km^2, accounts for the highest groundwater potential, serving as the most important aquifer for water supply. Based on the latest study conducted by the national project of "Groundwater Protection in the Big Cities, Hanoi", the detailed descriptions of the current groundwater extraction and situation in Hanoi have been comprehensively investigated by National Center for Water Resources Planning and Investigation (NAWAPI) under the supervision of the Ministry of Natural Resources and Environment in 2017 (NAWAPI2017 Project). The total groundwater extraction in Hanoi is about 1,129,249 m^3/day, in which PCA is the major aquifer for this withdrawal. As reported in another national water resource monitoring and investigation project from NAWAPI (1995–2014), the groundwater recharge varies from region to region, with a minimum of 85 mm/year in Hoang Mai district, a maximum of 1028.52 mm/year at Tay Ho district, and an average recharge estimation of about 276 mm/year (equal to 2,513,868 m^3/day). We also revealed the serious decline in groundwater levels. Specifically, the estimated area with occurrences of decreased groundwater levels is approximately 634.79 km^2, accounting for about one-fifth of the target area (NAWAPI, 2017). More seriously, the area with groundwater level less than 5 m (suggested by Hanoi's No.161/QĐ-UBND) from the threshold level reaches almost half (44%) of the HUA area. This critical zone includes Ung Hoa, Phuc Tho, Hoai Duc, Nam Tu Liem, Ha Dong, Thanh Oai, and My Duc districts (Fig. 1), which are in

Fig. 1. Study area and main rivers and lakes in Hanoi (Source: Bui et al., 2018).

danger of wiping away groundwater resources, according to the latest report of current groundwater problems in Hanoi from NAWAPI (2017). Consequently, land subsidence occurs over half of Hanoi, in which the most serious areas at the rate of more than 1.0 mm/year focused on Cau Giay, Ba Dinh, Tay Ho, Nam Tu Liem, and Thanh Xuan districts (Fig. 1). In terms of quantity, the environmental impact areas in HUA are thus more serious than the ones in PCA. The rapid groundwater exploitation without an appropriate management system has been considered a significant cause of these adverse impacts (Bui et al., 2012b). Regarding environmental impacts of groundwater over-exploitation, Phi and Strokova (2015), and Nguyen and Nguyen (2004) found that the land surface in Hanoi had subsided at an average rate of about 0.02 m/year, focusing on the central and south parts of Hanoi. As an economic and political center of Vietnam, Hanoi has been experiencing dramatic increases in population, agricultural and industrial activities, and urbanization, which also puts much more stress on groundwater quality (Li et al., 2017).

The Hanoi groundwater resource is reported to be a seriously degraded source with regards to both quantity (Bui et al., 2012b; NAWAPI, 2017) and quality (Berg et al., 2001; NAWAPI, 2017; Nguyen et al., 2015b), as consequences of inappropriate usage and management. As for the results of a series of our groundwater quality assessment studies in Hanoi and its adjacent provinces, the resource has been found to be seriously contaminated mainly by arsenic, nitrogen, iron, and manganese, in which iron- and manganese-contaminated areas account for one-third of Hanoi (Berg et al., 2001, 2008; NAWAPI, 2017; Nguyen et al., 2015a; Nguyen et al., 2015b; Nguyen et al., 2015c). Saltwater intrusion is also a concern in this area. The groundwater areas in PCA are likely more contaminated (about 50 times in terms of arsenic, 2 times in terms of nitrogen, and 1.2 times in terms of iron and manganese contamination) and intruded (2.4 times in terms of salt intrusion) than the ones in HUA. There are a series of publications and government reports concerning arsenic contamination of groundwater and its adverse human health impacts in Hanoi and its surroundings. The Hanoi government tries hard to not only control the ever-increasing groundwater abstraction and improve the current groundwater quality, but also recommends that the communities use advanced water purifiers as the best treatment system, and/or the sand filter metal removal technique, before using the water for domestic purposes (Bui et al., 2018).

3. Methodology

AHP was created by Saaty (2000) as an outstanding multicriteria decision making (MCDM) approach, which has been successfully applied in various sustainability applications. The commonly used AHP approach includes four basic steps in sustainability assessment. The first step in standard AHP applications is to create a hierarchy of components by breaking down the ultimate goal, the MCDM problem of sustainability, into its component features (criteria, aspects of each criterion, and indicators of each aspect). The second step is to assign a weight to the relative contribution of each component to the sustainability goal by consulting experts. Experts are asked to make, and even repeatedly make, a series of pairwise comparison judgments until acceptably-consistent judgments are obtained. The third step is to collect the actual data and obtain their transformation. The input indicator values vary, so a transformation method is needed to make those values dimensionless and within the range of 0–1. The transformed values are then automatically considered as the indicator sustainability indices. The fourth step is to assess the sustainability performance (Bui et al., 2018).

The following parts of this study clearly present the proposed AHP sustainability assessment for groundwater (AHP-SAG) via the following steps:

3.1. Step 1: build up a sustainability hierarchy

Similar to conventional AHP applications in sustainability assessment, decision-makers need to review and study the current situation and the complex MCDM problems (in this case, sustainability of groundwater) intensively to define groundwater sustainability criteria (GSC). This should cover all the features of the final sustainability goal, groundwater sustainability aspects (GSAs), which should cover all dimensions of the corresponding criterion, and then break down the GSAs into the corresponding groundwater sustainability indicators (GSIs). The GSIs should be the smallest component of the hierarchy and should be physically measurable.

3.2. Step 2: modified weighting process

Generally, as mentioned in conventional AHP applications, the weights refer to the relative contributions of the components to the final goal of sustainability. The conventional way of determining these relative contributions is very tedious due to the need to (i) find the appropriate experts, (ii) wait for them to make the large series of pair-wise comparison judgments, especially in the case of a large indicator set, and even (iii) ask the experts to repeatedly make the judgments until acceptably-consistent judgments are obtained. However, this expert-based weighting also "poses a genuine problem" because this weighting objective is to make many pairwise comparisons for incomparable components (Nardo et al., 2005). In developing countries like Vietnam, however, carrying out such complicated surveys regarding groundwater sustainability is difficult without enough financial support. Therefore, as our primary objective is to propose a groundwater sustainability assessment framework, this study was built on our previous studies (Bui et al., 2016, 2018) to make the conventional AHP simple by flexibly weighting the contributions of GSC, GSAs, and GSIs to the final goal. In this simple AHP approach, weights are derived as a function of the number of GSC, GSAs, and GSIs. For the simplest weighting case, particularly in this study, the GSC, GSAs, and GSIs were equally evaluated in an initial trial by using equations (1)–(3).

$$W_C(i) = \frac{1}{N} \tag{1}$$

$$W_A(i,\ j) = \frac{1}{N_i} \tag{2}$$

$$W_I(i,\ j,\ k) = \frac{1}{N_{ij}} \tag{3}$$

with the constraints:

$$0 \leq W_C(i);\ W_A(i,\ j);\ \ W_I(i,\ j,\ k) \leq 1 \tag{4}$$

$$\sum_{i=1}^{N} W_C(i) = 1;\ \sum_{j=1}^{N_i} W_A(i, j) = 1;\ \sum_{k=1}^{N_{ij}} W_I(i, j, k) = 1 \tag{5}$$

where $W_C(i)$: the weight of the *i*th criterion; $W_A(i, j)$: the weight of the *j*th aspect in the *i*th criterion; and $W_I(i, j, k)$: the weight of the *k*th indicator in the *j*th aspect of the *i*th criterion. *N*: number of the criterion; N_i: number of the aspects in the *i*th criterion; N_{ij}: number of indicators in the *j*th aspects of the *i*th criterion $i = 1 \ldots N$; $j = 1 \ldots N_i$; $k = 1 \ldots N_{ij}$.

Note that this equal weighting was not performed by the standard AHP approach. In this study, GSCs were selected as the three main sustainability pillars (environmental, social, and economic); it is clearly difficult to judge which criterion is more important than another in contributing to the sustainability goal. Similar to the three proposed GSAs (quantity, quality, and management) of the environmental criterion addressed later in section 4, it is also difficult to judge whether one aspect is more important than another, even within one environmental criterion. So equal weights are assigned to the three criteria and to the three main aspects of the environmental criterion. In terms of assigning weights for GSIs, pairwise comparisons based on the standard AHP is recommended if there is enough financial support and available relevant experts, so that a more appropriate weighting process for GSIs could be considered the final result. Regarding this special modification, once the GSC, GSAs, and GSIs are determined, the necessary weights are derived automatically by the number of GSC, GSAs, and GSIs. This equal-weighting process thus provides a quick view of the current groundwater status and can be easily applied to other areas.

3.3. Step 3: Data collection and SIF

Similar to the case of conventional AHP sustainability assessment application, the third step of the proposed AHP-SAG approach is to collect the actual data for evaluating the indicator values. The concept of sustainability index function (SIF) of an indicator was introduced in our previous study (Bui et al., 2018) to clarify the relationship between the indicator value and its sustainability index. Normally, sustainability indices have varied from 0 to 1 in the literature (Bui et al., 2017a,b; Pandey et al., 2011; Si et al., 2010; Singh et al., 2007). When the sustainability index for an aspect/indicator is 1, the criterion/aspect/indicator is assessed at the most excellent sustainability level (ideal sustainability). A sustainability index of zero, on the other hand, indicates the poorest sustainability level. The poorest sustainability level of the indicator/aspect/criterion/sustainability goal with an index of zero means that the indicator/aspect/criterion/sustainability goal is unsustainable. For instance, as shown in section 4, the SGI_{11} indicator is related to the relationship between groundwater abstraction and recharge. Reasonably, GSI_{11} should be at the lowest environmental sustainability index of zero when the abstracted groundwater is higher than the groundwater recharge. In this study, the sustainability

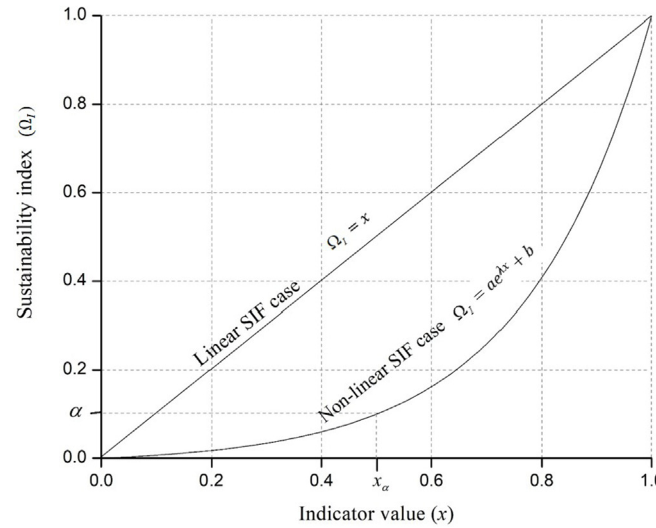

Fig. 2. Visualization of the conventional linear and non-linear SIF cases.

indicator should be defined in the way that the larger values of the indicators are, such that a stronger contribution can be made to the sustainability aspect, criterion, and goal. The final sustainability index is denoted Ω; the sustainability indices for criteria, aspects and indicators are denoted as Ω_C, Ω_A and Ω_I, respectively. The indicator is expressed as a dimensionless value (x) from 0 to 1, and Ω_I is a function of x.

Fig. 2 shows the visualization of SIF for two cases, which are named linear SIF and non-linear SIF.

In the case of linear SIF, which is normally used in conventional AHP applications, SIF is defined as a linear relationship between the indicator value (x) and its sustainability index (Ω_I). In this case, the SIF is expressed as follows.

$$\Omega_I(x) = x \tag{6}$$

In the case of non-linear SIF, SIF is defined by a non-linear relationship between the indicator value (x) and its sustainability index (Ω_I). The unknown function should satisfy three base conditions: (i) it is a monotonically increasing function with x, (ii) it should be zero at $x = 0$, and (iii) it should be 1 at $x = 1$. To satisfy these three conditions, any type of function is acceptable. Thus, the general exponential function is applied in this study, as follows.

$$\Omega_I(x) = ae^{\lambda x} + b \tag{7}$$

where *a*, *b* and λ are coefficients.

The unknown exponential function (Eq. (7)) is specified if its coefficients (*a*, *b*, and λ) are determined. A pair of x_α and α represents a point on this unknown exponential curve, and to determine its coefficients, at least three pairs of x_α and α are needed. Two critical points of ($x_\alpha = 0$; $\alpha = 0$) and ($x_\alpha = 1$; $\alpha = 1$) based on the abovementioned conditions, are already specified. Thus, an unknown pair of (x_α and α) must be determined by decision makers, depending on their specific interests, satisfying Eq. (8). The pair of x_α and α differs from problem to problem.

$$\Omega_I(x_\alpha) = \alpha \tag{8}$$

3.4. Step 4: sustainability assessment

The sustainability index $\Omega_I(i, j, k)$ of the *k*th indicator in the *j*th aspect of the *i*th criterion is evaluated based on specific considerations for the criteria, aspects, indicators, and the sustainability goal. Once all components of the sustainability hierarchy and the SIF for indicators are determined, $\Omega_I(i, j, k)$ can be calculated simply according to the

Table 1
Sustainability scale.

Proposed by Pandey et al. (2011)		Modified by Bui et al. (2016; 2017b; 2018)		
5-point score	Sustainability qualitative description	Scale	Sustainability level	Sustainability index range
0.00	Very poor	1	Very poor	$0 < \Omega_I,\ \Omega_A, \Omega_C,\ \Omega\ \le 0.2$
0.25	Poor	2	Poor	$0.2 < \Omega_I,\ \Omega_A, \Omega_C,\ \Omega\ \le 0.4$
0.50	Acceptable	3	Acceptable	$0.4 < \Omega_I,\ \Omega_A, \Omega_C,\ \Omega\ \le 0.6$
0.75	Good	4	Good	$0.6 < \Omega_I,\ \Omega_A, \Omega_C,\ \Omega\ \le 0.8$
1.00	Excellent	5	Excellent	$0.8 < \Omega_I,\ \Omega_A, \Omega_C,\ \Omega\ \le 1.0$

actual data. The sustainability index $\Omega_A(i, j)$ for the ith aspect and the final sustainability index Ω are evaluated by using the following equations (12)–(14), respectively.

$$\Omega_A(i, j) = \sum_{k=1}^{N_{ij}} W_I(i, j, k) * \Omega_I(i, j, k) \tag{12}$$

$$\Omega_C\ (i) = \sum_{j=1}^{N_i} W_A(i,\ j)^* \Omega_A(i,\ j) \tag{13}$$

$$\Omega = \sum_{i=1}^{N} W_C(i) * \Omega_C(i) \tag{14}$$

Therefore, naturally, the sustainability indices Ω, Ω_C, Ω_A, and Ω_I are within the range of 0–1. In addition, as suggested by Pandey et al. (2011), the situation of each sustainability component in terms of achievement of groundwater infrastructure sustainability, is classified in a crisp scale shown in Table 1. However, such crisp numbers corresponding to qualitative judgments (human preferences in this case) seems not always appropriate because crisp numbers have limitations in dealing with uncertainties of human preferences (Bui et al., 2017a; Levary, 1998). Therefore, Bui et al. (2016; 2017b; 2018) proposed a modified sustainability scale in a way that a qualitative score corresponds to a range of sustainability indices (Table 1), and this study adopted the later sustainability scale to support further sustainability assessment.

4. Demonstration of environmental sustainability assessment for groundwater resources in Hanoi

In the AHP approach, generally, the most important step is to identify the main components in the sustainability hierarchy (step 1). The three main sustainability pillars, environmental, social, and economic (Brundtland, 1987), are considered to be the three groundwater sustainability criteria in the hierarchy. The next levels are the aspects, associated with the indicators in each aspect. To identify the relevant environmental sustainability issues, it is essential to explore the current problems of groundwater usage and management in Hanoi from an environmental point of view. In sub-section 2.2 of this paper, the current environmental problems of groundwater resources in Hanoi have already been presented. These quantity and quality degradations have adverse impacts on the sustainable aquifer system and natural environment, which makes determining how to direct and manage the resource development toward sustainability a challenging task for the Hanoi government. Based on our previous study, Bui et al. (2018), we chose quantity, quality, and management as the three main aspects of groundwater sustainability. Therefore, in this study, the considerations of groundwater quantity, quality, and management concepts were also deemed to be the three main GSAs when reviewing the focal features of the environmental sustainability target. It is quite difficult to judge which GSA has a more important contribution to the environmental sustainability goal than another one, so in this study the three GSAs were given equal importance. We then carefully selected GSIs for each GSA based on the consideration of the current situation's actual problems and expected goals in the target area. A more complex indicator system could be developed if more actual reliable data were available.

Data are essential to developing integrated approaches for sustainable groundwater management (Rossetto et al., 2007). In a developing country like Vietnam, however, data related to the sustainability of groundwater management is sparse, seldom systematically organized, and accessible to a very limited number of official personnel (Bui et al., 2018). In this study, we exerted much effort to gathering the necessary data and, more importantly, to keeping the data consistent. The primary data sets came from the Vietnamese government database, and local and national environmental agencies. The input data we used are authorized and reliable, coming from the abovementioned national NAWAPI2017 Project, The Ministry of Science and Technology in 2017, Hanoi Statistics Office in 2017, Hanoi Sewerage and Drainage Limited Company in 2017, and several Hanoi groundwater targeted studies in 2014 and 2015. Therefore, the input data used in these proposed indicators are reliable for the 4-year period of (2014–2017) in Hanoi, Vietnam. Based on the criteria of data availability and reliability, low reliability data (too old or from the unpublished works) were screened out, and only up-to-date, authorized, and reliable data were utilized for indicator development.

The quantity aspect (GSA_1) is a measure of the amount of abstracted groundwater compared to its recharge, exploitable amounts, and consequences of groundwater over-exploitation. As guided by the UNESCO/IAEA/IAH Working Group (Vrba and Lipponen, 2007), the indicators regarding the ratio of abstraction to recharge and to exploitable groundwater resources, are mainly used to assess groundwater sustainability in a quantitative measurement. However, in this study, in order to define the GSIs which follow the rule of “the bigger the GSI value, the better its contribution to the environmental sustainability goal”, the first two indicators of the quantity aspect are defined as follows.

$$GSI_{11} = \begin{cases} 1 - \frac{Total\ abstraction}{Total\ recharge} & if\ \ the\ \ abstraction \le the\ \ recharge \\ 0 & if\ \ the\ \ abstraction > the\ \ recharge \end{cases} \tag{15}$$

$$GSI_{12} = \begin{cases} 1 - \frac{Total\ abstraction}{Exploitable\ groundwater} & if\ \ the\ \ abstraction\ \le the\ \ exploitable \\ 0 & if\ \ the\ \ abstraction\ > \ the\ exploitable \end{cases} \tag{16}$$

For these definitions, the environmentally-sustainable contributions of GSI_{11} and GSI_{12} are maximized at values of one if there is no groundwater abstraction and minimized at zero values for the occurrence of groundwater over-exploitation. For the next three indicators GSI_{13}, GSI_{14}, and GSI_{15}, according to the current situation of groundwater problems presented in section 2.2, these indicators are focused on areas of groundwater decline, critical zones (area with the groundwater levels less than 5 m (suggested by Hanoi's No.161/QĐ-UBND from the threshold level), and land subsidence areas, respectively. By these index-based definitions, these indicator values are in the range of 0–1 and follow a positive correlation with their sustainability indices. The indicators of the first aspect (GSA_1) and their index-based definitions are shown in Table 2.

Table 2
Environmental sustainability aspects and indicators for Hanoi groundwater resources.

GSA	GSI	Consideration	Index-based definition
Quantity (GSA_1)	GSI_{11}	Abstraction-recharge relation	One minus the ratio of groundwater abstraction to groundwater recharge if this ratio is less than 1, otherwise 0
	GSI_{12}	Abstraction- exploitable relation	One minus the ratio of groundwater abstraction to exploitable groundwater resources if this ratio is less than 1, otherwise 0
	GSI_{13}	Declined level	One minus the proportion of area with decline of groundwater level caused by groundwater over-exploitation
	GSI_{14}	Critical zone	One minus the proportion of area with the groundwater levels less than 5 m (suggested by Hanoi's No.161/QĐ-UBND) from the threshold level
	GSI_{15}	Land subsidence	One minus the proportion of area with land subsidence occurrence caused by groundwater over-exploitation
Quality (GSA_2)	GSI_{21}	Arsenic contamination	One minus the proportion of area with arsenic-contaminated groundwater
	GSI_{22}	Nitrogen contamination	One minus the proportion of area with ammonium, nitrate dioxide and nitrate-contaminated groundwater
	GSI_{23}	Fe and Mn contamination	One minus the proportion of area with iron and/or manganese contaminated groundwater
	GSI_{24}	Saltwater intrusion	One minus the proportion of area with groundwater salt intrusion
Management (GSA_3)	GSI_{31}	Reducing pressure	Proportion of budget allocation for reducing pressure on groundwater resources
	GSI_{32}	Environmental law enforcement	Proportion of environmental law obeyed
	GSI_{33}	Water-related human capacity	Proportion of the current number of people who are working for water related field

Quality aspect GSA_2 is a measure of the proportion of contaminated groundwater in the target area. As guided by the UNESCO/IAEA/IAH Working Group (Vrba and Lipponen, 2007), these indicators should be defined as the ratios between the contaminated areas due to natural and anthropogenic causes to the total areas. Due to the data availability and reliability, in this aspect we only consider the major groundwater problems in Hanoi to propose the indicators of GSA_2. In the literature of groundwater quality in Hanoi, recent concern is for the four major contaminants of arsenic, nitrogen, iron and manganese, and saltwater intrusion. Based on the unique data from the abovementioned NAWAPI2017 Project regarding groundwater protection in Hanoi, the related area estimation of these contaminations was reported. So, for this quality aspect, four indicators needed to be considered to measure the percentage of these contaminated/intruded areas to the total study area. For example, the first indicator, GSI_{21}, of this quality aspect corresponds to arsenic contamination. It is defined as one minus the proportion of the study area with arsenic-contaminated groundwater to make its value within the range of 0–1 and follow the positive correlation with its sustainability index (Table 2). Similar index-based definitions for the other quality indicators, nitrogen, iron, and manganese, and saltwater intrusion, are also defined.

For the management aspect, GSA_3, we consider how the local government manages and improves the current environmental situation, and how the implementation of the water-related policies and regulations is being handled, because the legislation does not always translate into implementation. The three indicators of the management aspect are about (i) how the government reduces pressure on groundwater resources while still fulfilling social needs, (ii) how much in percentage the environmental laws are obeyed in actual implementation, (iii) the strength of the current human resources in the water-related fields specifically, and in the natural resources and environmental fields generally. Finally, the three main GSAs (quantity, quality, and management) and their five, four, and three corresponding GSIs, respectively, are shown in Table 2. These factors are proposed to build the environmental sustainability hierarchy for Hanoi groundwater based mainly on consideration of the current problem from an environmental point of view.

5. Results and discussion

According to the index-based definitions of the indicators described in the previous section, the indicator values were then calculated, as shown in Table 3. The following sub-sections explain procedures for obtaining the environmental sustainability indices (ESIs) for Hanoi groundwater from both a conventional linear relationship and non-linear SIF. Hereafter, the conventional relationship is expressed as the linear SIF.

5.1. The linear SIF case

In the case of the linear SIF in Eq. (8), each indicator value x is taken as its ESI Ω_I. The ESIs of the aspects, Ω_A, and the final ESI Ω, are calculated by Eqs. (12) and (13), respectively. The resulting indices are shown in the column for the linear SIF case in Table 3.

In the quantity aspect (GSA_1), GSI_{11}, and GSI_{12} are assessed, respectively, at acceptable and excellent sustainability levels of 0.541 and 0.865, according to the sustainability scale shown in Table 1. These assessments indicate that the proportion of groundwater abstraction is quite small compared to groundwater recharge (about 46%) and groundwater exploitable resources (about 13.5%). As guided by UNESCO/IAEA/IAH (Vrba and Lipponen, 2007), groundwater can be considered "low development" if the abstraction-exploitable ratio is less than 90%. For the abstraction-recharge ratio, even if the abstraction is equal to the recharge, there will be also no environmental impacts of groundwater level decline. From the environmental point of view, the less groundwater abstracted, the better the ESI. In the Hanoi case, therefore, corresponding to the "low" status of groundwater development, the GSI_{11} value of 0.541 should be assessed as excellent sustainability level, and the abstraction amount could be increased even more than the current level to meet social needs. In short, the sustainability assessment of GSI_{12} is reasonable, while the one for GSI_{11} is not quite suitable to reflect the "low development" of Hanoi groundwater. The indicator GSI_{13} is assessed at the excellent sustainability level of 0.810, suggesting that the areas with groundwater levels that have been declined occupied about 20% of Hanoi. The indicators GSI_{14} and GSI_{15} are also assessed, respectively, at good and acceptable sustainability levels of 0.766 and 0.420, illustrating the critical zone and the areas with the occurrence of land subsidence are, respectively, more than one-fifth and more than half of Hanoi. Looking back to the current environmental issues presented in section 2.2 in the study area, the critical zone (the depleted zone and the zone in danger of depletion) occupied almost half of the HUA aquifers, in which more than half of it is depleted. Dealing with this critical situation, in the act No. 161/QD-UBND released in 2012, Hanoi government decided to reduce and even suspend groundwater withdrawal in these critical zones. Thus, the good ESI for the indicator GSI_{14} is not quite suitable in the Hanoi case and more appropriate assessment is needed to reflect the actual situation reasonably. Consequently, the ESI of the quantity aspect, GSA_1, is assessed at a good level $\Omega_A(1)$ of 0.680.

Similarly, in the quality aspect (GSA_2), all the indicators are assessed at a more than acceptable sustainability level. The first three indicators related to arsenic, nitrogen, and other metal (Fe and Mn) contaminations are, respectively, assessed at excellent, excellent, and good sustainability levels. The last indicator $GSI_{24,}$ related to saltwater intrusion, is also assessed at an excellent level of 0.899. As a result, the sustainability index of the quality aspect is assessed at an excellent level

Table 3
Environmental sustainability assessment for Hanoi groundwater resources.

GSA	$W_A(i)$	GSI	$W_I(i,j)$	GSI value (x)	Linear SIF case			Combined linear & non-linear SIF case		
					Ω_I	Ω_A	Ω_l	Ω_I	Ω_A	Ω
Quantity (GSA_1)	0.33	GSI_{11}	0.20	0.541	0.541	0.680 (Good)	0.665 (Good)	0.919	0.525 (Acceptable)	0.506 (Acceptable)
		GSI_{12}	0.20	0.865	0.865			0.865		
		GSI_{13}	0.20	0.810	0.810			0.427		
		GSI_{14}	0.20	0.766	0.766			0.350		
		GSI_{15}	0.20	0.420	0.420			0.067		
Quality (GSA_2)	0.33	GSI_{21}	0.25	0.912	0.912	0.841 (Excellent)		0.675	0.521 (Acceptable)	
		GSI_{22}	0.25	0.850	0.850			0.511		
		GSI_{23}	0.25	0.701	0.701			0.260		
		GSI_{24}	0.25	0.899	0.899			0.637		
Management (GSA_3)	0.33	GSI_{31}	0.33	0.630	0.630	0.473 (Acceptable)		0.630	0.473 (Acceptable)	
		GSI_{32}	0.33	0.163	0.163			0.163		
		GSI_{34}	0.33	0.625	0.625			0.625		

of 0.841. Thus, based on the linear SIF of Eq. (6), for example, regarding the risk of arsenic contamination of groundwater, if 50% of the area is at risk, the sustainability index will be assessed at the acceptable level of 0.5. Besides, from a quality point of view in the study area, there are a series of publications and government reports concerning arsenic, nitrogen (especially NH_4^+), and other metal (Fe and Mn) contamination of groundwater and its adverse human health impacts in Hanoi and its surroundings. The government tries hard to control the ever-increasing groundwater extraction in certain areas in Hanoi and raise public awareness about this serious situation via their various communication media. The communities are advised to use advanced water purifiers in the urban districts and the sand-filter arsenic removal technique in the suburban districts before using the water for domestic purposes (Bui et al., 2018). Therefore, the ESIs based on the linear SIF of the indicators regarding the risk of contaminated areas, is inappropriate considering the severe groundwater pollution problems in Hanoi. There is a gap between the environmental sustainability assessment and its ability to reflect the actual groundwater quality problems in Hanoi.

In the management aspect (GSA_3), GSI_{31}, and GSI_{33} are assessed at a good sustainability level, showing that the government of Hanoi has recently given much attention to both reducing the high pressure on groundwater resources and strengthening their human capacity in natural resources and environment fields. On the one hand, they continuously finance several surface water treatment plants (reaching approximately 516.6 million USD in 2014–2017, according to the Ministry of Science and Technology (2015)) that take water sources from rivers in and near the capital. These projects are projected to reduce the current high pressure on groundwater resources once fully operating. In addition, they also have expanded their water/natural resources and environment authorities (universities, institutes, national centers, etc.) to enhance education of the relevant human resources. However, as is often the case regarding law enforcement in the developing countries like Vietnam, the environmental enforcement is quite lax in implementation. In Hanoi's case, while the government regulations require all industrial zones to have their own wastewater treatment stations, only about half of them (55.8%) obey, according to Hanoi Sewerage and Drainage Limited Company (HSDC) (2017). HSDC (2017) also mentioned that in such 55.8% of the industrial zones, there are several wastewater treatment plants which have been inactive for 10 years. As another example, only 10% of the domestic wastewater and 30% of the wastewater from local hospitals and manufacturing facilities in Hanoi are appropriately treated before discharge into water bodies. As a result, the ESI of GSI_{32} is assessed at a very poor level of 0.163. Consequently, from the linear SIF case, the ESI of the management aspect is at the acceptable level of 0.473. This assessment makes sense not only in terms of environmental sustainability but also from a social point of view because, as we explored via our social survey in 2014, only 6% of respondents rated government management at a good level, more than half of them (51%) rated the performance at an acceptable level (Bui et al., 2018). Generally, the ESI using the linear SIF, $\Omega_C(l)$ of groundwater in Hanoi is assessed at a good level of 0.665 (Table 3).

5.2. The combined linear and non-linear SIF case

We continue to apply the linear SIF for the indicators of the management aspect (GSA_3) because the sustainability assessment based on the linear SIF seems to appropriately reflect the current management situation of groundwater development in Hanoi.

However, in the quantity aspect, as mentioned in sub-section 5.1, the ESIs based on the linear SIF of the indicator GSI_{11} do not suitably reflect the "low" status of Hanoi groundwater development. So, if the groundwater abstraction is 50% of the recharge (or the value of GSI_{11} is at $x_\alpha = 0.5$), its sustainability index α should be assessed at some value in the excellent sustainability range of 0.8–1.0) (Table 1). This study, hence, roughly assumed the following condition (Eq. (17)), by which, if 50% ($x_\alpha = 0.5$) of the groundwater recharge is abstracted, the sustainability index will be at the value of 0.9 ($\alpha = 0.9$).

$$\Omega_I(x) = -1.0125e^{-4.3944x} + 1.0125 \tag{17}$$

In addition, for the quantity aspect, as mentioned in sub-section 5.1, the indicators regarding groundwater depletion (decreased groundwater level GSI_{13} and critical zone GSI_{14}) and its environmental impacts (land subsidence occurrence GSI_{15}) were not appropriately assessed based on the linear SIF case. For example, if 50% ($x_\alpha = 0.5$) of Hanoi is in the critical zone, from an environmental sustainability point of view, its sustainability index should be assessed at some values in the very poor range levels of 0–0.2 (Table 1). We thus roughly take the judgment Eqs. (18) and (19) of ($\alpha = 0.1$ at $x_\alpha = 0.50$) for the critical zone indicator GSI_{14} of the quantity aspect GSA_1.

$$\Omega_I(x_\alpha = 0.5) = 0.1 \tag{18}$$

$$\Omega_A(x) = 0.0125e^{4.3944x} - 0.0125 \tag{19}$$

The values of α and x_α totally depend on the interests of decision-makers, which are different from situation to situation and from indicator to indicator. To have better assessment results, each indicator should be judged individually. However, as the first trial for the Hanoi case study, we here also use Eqs. (18) and (19) for the declined level GSI_{13} and land subsidence occurrence GSI_{15} indicators.

Similar to the indicators of the quality aspect GSA_2, to fill the gap between the environmental sustainability index and its ability to reflect the actual quality situation, a more reasonable judgment for the indicators in GSA_2 is needed. Regarding the area at risk of arsenic groundwater contamination, for example, if 50% ($x_\alpha = 0.5$) of the Hanoi area is at risk of the contamination, its environmental

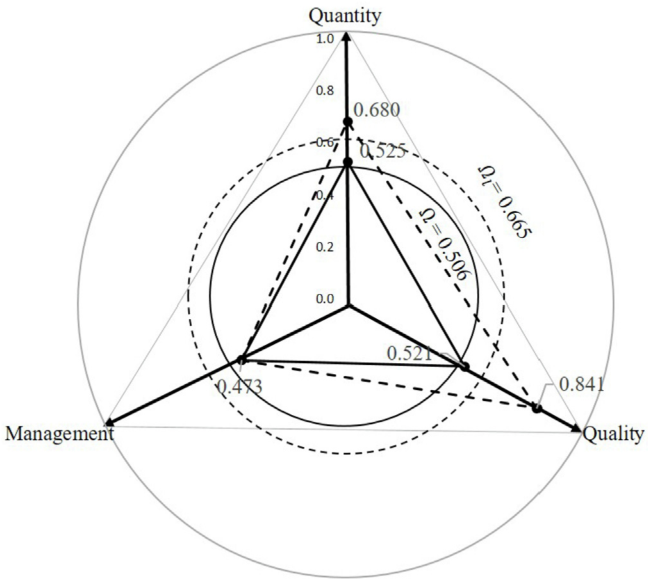

Fig. 3. Visualization of the environmental sustainability assessment results obtained by the conventional linear and the combined linear and non-linear SIF cases.

sustainability index should be assessed at some values in the very poor range of 0–0.2 (Table 1). This study, hence, roughly assumed an Eq. (18) condition, by which, if 50% ($x_\alpha = 0.5$) of the area is at this risk of arsenic groundwater contamination, its sustainability index will be assessed at a very poor value of 0.1 ($\alpha = 0.1$). We, then, also applied Eq. (19) for other quality indicators regarding areas at risk of nitrogen and iron and manganese contamination of the quality aspect.

Using the same value x as shown in Table 3, we could get all the ESIs for GSI_{13}, GSI_{14}, GSI_{15} of the quantity aspect and the four indicators in the quality aspect using Eqs. (17) and (19). The ESIs for Ω_A and the final ESI Ω_C were then calculated correspondingly using Eqs. (12) and (13). Those resulting sustainability indices are shown in the column for "Combined linear and non-linear SIF case" in Table 3. The results in this case are also shown in Fig. 3 as a solid line in the radar chart.

From the quantity aspect of Table 3, the indicator regarding the abstraction-recharge relation is significantly improved to an excellent sustainability level of 0.919, compared to the one based on the linear SIF. This assessment is well matched with the general "low development" of Hanoi groundwater. In contrast, other indicators related to groundwater depletion, GSI_{13}, $GSI_{14,}$ and GSI_{15} in this quantity aspect, are relatively reduced to poor or even very poor sustainability levels. This dissimilar situation reveals the actual problems of Hanoi groundwater development: generally, the resource development is "low" but locally the resource is over-exploited and depleted. Therefore, a recommendation for sustainable groundwater development is to re-distribute appropriately the groundwater abstraction networks over the whole area, by which the groundwater abstraction could be increased immensely to utilize the naturally-rich recharge benefiting from the local tropical climatic features without making the currently-adverse environmental adverse impacts resulting from groundwater over-exploitation and depletion more serious. Consequently, the ESI of the quantity aspect is appropriately assessed at an acceptable sustainability level of 0.525.

Similar to the quality aspect, all indicators are significantly reduced compared to those based on the linear SIF case. Specifically, the indicator related to metal contamination, GSI_{23}, is assessed at a poor sustainability level of 0.260, reflecting the current serious metal pollution in Hanoi groundwater. These assessment results for the quality aspect appropriately reflect the current quality situation (presented in sub-section 2.2), because these sustainability indices reflect the actual quality problems more reasonably. As a result, the ESI of the quality aspect is appropriately assessed at the acceptable sustainability level of 0.521. Additionally, the non-linear SIF of Eq. (19) could suggest an acceptable environmental sustainability threshold (EST) for groundwater contamination in developing countries like Vietnam. As shown in Table 1, 0.4 is the minimum sustainability index value in the acceptable sustainability range of 0.4–0.6. The corresponding indicator value of this minimum acceptable sustainability index is calculated as 0.8 based on Eq. (19). Therefore, the contamination of groundwater could be considered an environmentally acceptable sustainability if at least 80% of an areas is not at that risk. This acceptable EST value is necessary to enable policymakers to understand the basic environmental challenges and give an early warning to communities.

Consequently, the final ESI, $\Omega_C(nl)$ for Hanoi groundwater is appropriately assessed at the acceptable level of 0.506 in this case (Table 3). Fig. 3 clearly shows the difference in the sustainability assessment results between the linear and the combined linear and non-linear SIF cases. In terms of the assessment reflecting the actual situation, the sustainability assessment results based on the combined linear and non-linear SIF are more reasonable. The final ESI, $\Omega_C(nl)$, shows an environmentally-acceptable overview of the sustainability of Hanoi groundwater development and management. It also indicates that improving the current quality, and strictly enforcing the environmental laws and regulations, are the key processes for ensuring a feasibly-sustainable groundwater resource in Hanoi.

6. Conclusion

To the best knowledge of the authors, this study is the first attempt to develop a groundwater sustainability assessment framework based on the indicator-based AHP approach. To accomplish this, we modified the conventional AHP approach into the AHP-SAG approach. In the AHP-SAG, basically, the four major steps based on the conventional AHP application for sustainability assessment studies were followed. The three main sustainability pillars, environmental, social, and economic, were considered the three groundwater sustainability criteria in the hierarchy. The next levels were the aspects, associated with the indicators in each aspect. Equal weights were reasonably assigned to the three criteria and aspects to judge their importance to the final sustainability goal. The weighting step of AHP-SAG for indicators was simplified to adjust for the lack of enough financial support, data availability, and relevant experts in developing countries like Vietnam. Groundwater sustainability indicators were also developed in this way, supporting decision-makers in making their judgment of the component contributions to the final sustainability goal more easily. The concept of SIF is utilized to clarify the relationship between indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature. We then demonstrated the proposed AHP-SAG for environmental sustainability criterion of groundwater resources in a Hanoi case study for the first time. In this application, we proposed three practical sustainability aspects (quantity, quality, and management) and their twelve core environmental sustainability indicators, which appropriately represent the current environmental situation in Hanoi. We improved the environmental sustainability assessment by gathering available and reliable data to test linear and non-linear SIF cases. We successfully assessed the sustainability of groundwater in Hanoi from an environmental point of view.

These assessments based on the combined linear and non-linear SIF were more reasonable than those using conventional linear SIF alone, because the sustainability indices properly reflected the current groundwater problems in Hanoi from an environmental point of view. The variability of the environmental sustainability indices indicated that the current groundwater extraction networks are heavily concentrated in some specific areas in Hanoi, which is not optimal for utilizing the rich natural recharge of the area. Improving the current poor groundwater quality and the strict enforcement of environmental laws and regulations are essential to enhancing the environmental sustainability and, more importantly, to drive Hanoi towards sustainable groundwater resources. Therefore, these findings are indispensable for any further sustainability assessments of groundwater resources. However, Eqs. (17) and (19), regarding the fixed values of α and x_α applied to several indicators of the quantity and quality aspects, were used in the first stage for the Hanoi case study. For better sustainability assessment, each indicator in the aspect should be treated individually. The equal weights of the sustainability indicators were used to cope with the limited data availability in the study area. These limitations have implications for the results obtained from this study. If possible, with enough financial support and experts in the related fields, we could execute a more thorough process of weighing the relative contribution of each indicator by the standard AHP. Better assumptions applied differently for each indicator of an aspect, yielding a more appropriate weighting process, could be considered in future work.

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