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Social sustainability assessment of groundwater resources: A case study of Hanoi, Vietnam

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A R T I C L E I N F O

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A B S T R A C T

Groundwater plays a key role in public water supplies around the world, and consideration of the social dimension is a key issue in sustainable groundwater management. In Hanoi, the capital of Vietnam, the situation of groundwater resources is disastrous because the quality has seriously degraded recently. Hence, in this study, a social sustainability assessment framework of groundwater resources with a focus on Hanoi is proposed for the first time. An analytical hierarchy process (AHP) approach was used to generate the main components (aspects and indicators) of this framework, which has been considered one of the most challenging tasks in AHP sustainability applications. To overcome these challenging tasks, we carefully reviewed and explored the current problems of Hanoi groundwater resources to propose 3 main aspects (quantity, quality, and management) and appropriately selected their 13 sustainability indicators for this target area. We introduce a sustainability index function (SIF) for indicators to clarify the relationship between each indicator value and its sustainability index. Furthermore, we consider both the conventional linear relationship, as it is usually developed in the literature, as well as a non-linear SIF to arrive at a reasonable sustainability assessment. For the Hanoi case study, the sustainability indices obtained using a combined linear and non-linear SIF method reflect the current problems well, that is, the social sustainability assessment is closer to reality. The sustainability indices of the quantity, quality, and management aspects of the groundwater were appropriately assessed as good, poor, and acceptable, respectively, resulting in Hanoi being rated at the acceptable level in the final social sustainability assessment. This result reveals that the population of Hanoi is satisfied with the quantity of water but dissatisfied with its current poor quality and its relatively high price.

1. Introduction

Proper management of water resources is crucial for ensuring sustainable socioeconomic development of every country in the world (Hutton and Bartram, 2008). Ensuring safe and affordable drinking water for all is one of the universal targets of the 17 United Nations Sustainable Development Goals (United Nations, 2017). Groundwater plays a key role in water supplies worldwide. More than two billion people depend on groundwater for their daily water supply, and more than half of the global population depends on it for drinking purposes (United Nations, 2015). Groundwater sustainability refers to developing and using groundwater in ways that preserve the resource for an indefinite time without causing any adverse eco-environmental or social consequences (Alley et al., 1999). Put simply, groundwater sustainability means that groundwater of sufficient quantity and quality at an acceptable price is available to meet the social demands of the region without causing any environmental degradation (Plate, 1993). Because the amount of groundwater extraction has been increasing rapidly and continuously worldwide, achieving sustainable management of groundwater is one of the essential objectives for the future of many countries (Mende et al., 2007). The important questions are how to provide decision-makers with enough information to assist management decisions and how to recommend actions that should or should not be taken to improve groundwater sustainability. In order to find appropriate answers for the aforementioned questions, a sustainability assessment of groundwater resources, which is a challenging task, is

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required.

Sustainability assessment is generally considered a useful technique to help decision-makers determine the actions that they should or should not take in an attempt to make society sustainable (Devuyst et al., 2001). Among the sustainability assessment methodologies, multi-criteria decision making (MCDM) is considered to be the best approach for sustainability assessment (Boggia and Cortina, 2010), and analytical hierarchy process (AHP), an outstanding MCDM, is usually used for various sustainability assessment projects, including those for the mining sector (Bui et al., 2017; Singh et al., 2007), environmentally sustainable evaluation (Si et al., 2010), and regional water resources (Sun et al., 2016), due to its ability to cope with multifaceted and unstructured sustainability problems (Yu, 2002). The main advantage of such AHP applications is the ability to categorize and identify the foremost components (aspects and indicators) that best reflect the significant sustainability performance. In these indicator-based AHP applications for sustainability assessment, the outputs are expressed as sustainability indices because the indices can convey a straightforward message to stakeholders and policy-makers and also reveal the best practices and weaknesses of their development strategies (Ness et al., 2007; Pinar et al., 2014). In these studies, the indicator values themselves are usually taken as their sustainability indices. This consideration of the indicator values and their sustainability indices is not always appropriate because the indicator values depend on how the indicators are defined, and the sustainability indices should be converted from the indicator values depending on the specific interests of decision-makers. Therefore, it is necessary to introduce a concept to clarify the relationship between an indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature.

Among the three main pillars of the sustainability concept (including environmental, social and economic pillars (Brundtland, 1987)), the social criterion has specifically received less consideration than the economic and environmental criteria (Mani et al., 2016; Pinar et al., 2014; Vallance et al., 2011) because this concept is typically difficult to define and quantify. There is no specific definition of social sustainability, so each study defines the concept based on its own specific viewpoints. For example, Chiu (2003) and Vallance et al. (2011) agree that social sustainability refers to the improvement and maintenance of the well-being of both current and future generations. They emphasize that the concept refers to the social conditions necessary to support ecological sustainability and the equality requirement of rights of access to resources and social services. However, the meaning of the concept remains unclear, and additional investigations are needed (Axelsson et al., 2013). As one of the very few examples of AHP application to groundwater sustainability, the work of Chen et al. (2015) addresses assessment in the semiarid Hohhot Plain region of China. In their study, the adopted indicators focused mainly on the environmental perspective, and the social perspective is almost neglected as there is only a one-indicator consideration of population density. To date, there have been almost no studies utilizing the indicator-based AHP approach for groundwater sustainability assessment. Particularly for social sustainability assessment of groundwater, it is necessary to have a better understanding of the social demand and satisfaction of water usage as well as public attitudes toward a sustainable water resources management. Public responses and contributions are vital to ensure the protection of water resources and the success of any water conservation measure and policy (Dolnicar et al., 2011; Li et al., 2015). Hence, clearly defining such social indicators is indispensable for groundwater sustainability assessment.

To resolve the aforementioned problems, this study aims to (i) utilize the AHP concept to define an appropriate indicator set for the establishment of a groundwater sustainability assessment framework from a social perspective; (ii) introduce a sustainability index function (SIF) for clarifying the relationship between an indicator value and its sustainability index, as this relationship is not clear in the sustainability literature; and (iii) consider both the conventional linear relationship as it is usually examined in the literature and also a non-linear SIF to determine a reasonable sustainability assessment. For a better sustainability assessment, we describe how the social sustainability indices could reflect the actual situation of groundwater problems in the case study of Hanoi, Vietnam.

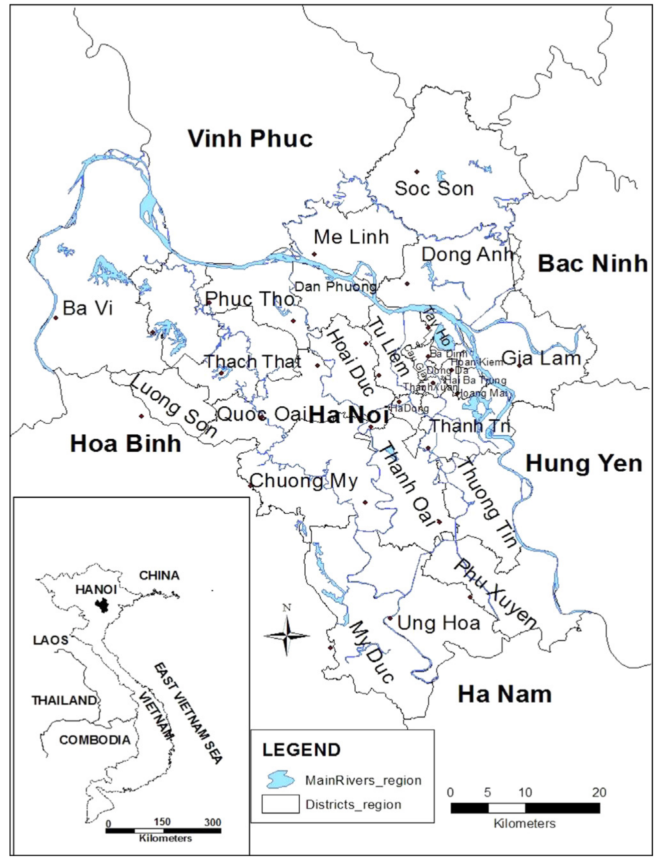

Fig. 1. Study area and main rivers and lakes in Hanoi.

2. Study area

2.1. Basic conditions of Hanoi

In Vietnam, groundwater has become the most important source of water supply, especially in the rapidly urbanizing capital of Hanoi, where most of the rivers and lakes are seriously polluted due to the discharge of untreated industrial, agricultural, aquacultural, and domestic waste (Bui et al., 2012a). The geographical location and the main rivers and lakes of Hanoi are displayed in Fig. 1. Hanoi, which is located in the northeastern part of Vietnam, covers an area of 3324.5 km^2. Its population of more than 7.2 million (2015) accounts for almost 10% of the total population of Vietnam, and its population density is more than 2000 people/km^2 (General Statistic Office of Vietnam, 2015), the highest in Vietnam. Hanoi is within the tropical monsoonal area with two distinctive annual seasons, the rainy season and the dry season. The annual average rainfall is about 1600 mm, the average humidity is about 80%, and the average temperature is about 24.3 °C. Evaporation is quite high, with an annual average of 933 mm. Hanoi, as part of the Red River Delta (RRD) with an area of 155,000 km^2, has a dense river network (0.7 km/km^2), and the rapid urbanization has put great pressure on the river basin environment.

2.2. Current situation of groundwater resources and domestic water use in Hanoi

According to our previous studies (Bui et al., 2011, 2012a) regarding groundwater quantity and the aquifer systems of Hanoi and the RRD, the groundwater resources of Hanoi exist mainly in the topmost Holocene unconfined aquifer (HUA) and the shallow Pleistocene confined aquifer (PCA). The HUA has a relatively high groundwater potential, sufficient for the small- to medium-scale domestic water supply. The PCA has the highest groundwater potential and is the most important aquifer for regional water supply. We also revealed a serious decline in the groundwater levels in this area. Rapid exploitation of the groundwater, without an appropriate management system, has been considered a significant cause of these adverse impacts (Bui et al., 2012b). The groundwater decline can be disastrous for those communities that tap their water from shallow wells. Even though excessive groundwater extraction has caused serious groundwater-level declines in the central and southern parts of Hanoi, insufficient water use is still reported in the city (HAWACO, 2016). In 2016, the public water utilities failed to supply urban districts approximately every two days per month (HAWACO, 2016). This insufficient water usage has adverse effects on the daily routines of the residents, especially in the summer season when the temperature can reach 45 °C in the urban districts. The economic and political center of Vietnam, Hanoi has been experiencing dramatic increases in population, agricultural and industrial activities, and urbanization, which also put substantial additional stress on the groundwater quality (Li et al., 2017).

According to HAWACO (2014), the largest water distribution company in Hanoi, 55% of the city's population, or 3.6 million users, have access to piped water, which is a quality-controlled source; the urban and suburban districts have 100% and 42% public water coverage, respectively. Although public water fully covers all the urban districts, about 30% of households still used freely accessed water from private and community wells without any quality standard in 2010 (UNDP, 2010). Unfortunately, this groundwater resource is seriously degraded in both quantity (Bui et al., 2012b) and quality (Berg et al., 2001; Nguyen et al., 2015b) as a consequence of inappropriate usage and management. According to the results of a series of our groundwater quality assessment studies in Hanoi and its adjacent provinces, the resource has been seriously contaminated by mainly arsenic, coliform, and nitrogen (Berg et al., 2001, 2008; Nguyen et al., 2014; Nguyen et al., 2015a; Nguyen et al., 2015b; Nguyen et al., 2015c). In the RRD, several million people consuming such untreated groundwater could face considerable health risks (Berg et al., 2001). These degradations of quantity and quality are thus threatening the community's goal of ensuring sustainable groundwater development because as much as 80% of diseases are reported to be caused by polluted water resources in Vietnam (VUFO-NGO Resource Centre, 2017). Even though 68% of Hanoi is covered by the public water supply system (PWSS) (HAWACO, 2014), as much as 45% of the population could not access public water in 2010 due to their low monthly incomes against water prices (Lucía et al., 2017). Consequently, these residents use alternative freely accessible but quality-uncontrolled groundwater resources. How to address the aforementioned difficulties of water usage in Hanoi communities is a big question for the management of water resources by the local government.

3. Methodology

3.1. The four major steps in standard AHP application for sustainability assessment

Established in the 1970s by Saaty (2000), AHP is one of the most powerful and popular MCDM methods for addressing multifaceted and unstructured problems such as those of the political, economic, social, and management sciences. The commonly used AHP approach includes four basic steps in sustainability assessment. The first step in standard AHP application is to create a hierarchy of components by breaking down the ultimate goal, the MCDM problem of sustainability, into its aspects and indicators of each aspect of sustainability. The second step is to assign a weight to the relative contribution of each aspect and indicator 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 to 1. The transformed values are then automatically considered as the indicator sustainability indices. The fourth step is to assess the sustainability performance.

3.2. The proposed SIF-AHP approach for groundwater sustainability assessment

The proposed AHP coupled with the sustainability index function (SIF) approach (SIF–AHP approach) is explained by the following four methodological steps.

Step 1: Build a sustainability hierarchy

As in the case of conventional AHP applications in sustainability assessment, decision-makers need to review and study the current situation and the complex MCDM problems (in this case, social sustainability of groundwater) intensively to define sustainability aspects (SAs), which should cover all of the features of the final goal, and break down the SAs into the corresponding sustainability indicators (SIs). The SIs should be the smallest component in the hierarchy and should be physically measurable. Defining SAs and SIs is among the most challenging tasks in AHP sustainability application.

Step 2: Modified weighting process

Generally, as mentioned in the conventional AHP applications, the weights refer to the relative contributions of the components to the final goal of sustainability. The conventional method of determining these relative contributions is very tedious due to the need to (i) find appropriate experts, (ii) wait for them to make the large series of pairwise comparison judgments, especially in the case of a large indicator set, and (iii) even ask the experts to make repeated judgments until acceptably consistent judgments are obtained. In developing countries such as Vietnam, however, carrying out such complex surveys regarding groundwater sustainability is often difficult because of insufficient financial support. Therefore, in our previous study (Bui et al., 2016), we modified the conventional AHP to make it simpler by flexibly weighting the contributions of SA and SI to the final goal. In this simple AHP approach, weights are derived as a function of the number of aspects and indicators. For the simplest weighting case, particularly in this study, the aspect and indicator weights are evaluated equally in the first trial by using Eqs. (1) and (2).

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

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

with the constraints:

$$0 \leqslant W_A(i),\ W_I(i, j) \leqslant 1 \tag{3}$$

$$\sum_{i=1}^{N} W_A(i) = 1;\ \sum_{j=1}^{N_i} W_I(i, j) = 1 \tag{4}$$

Where $W_A(i)$ is the weight of the i^{th} aspect; and $W_I(i, j)$:the weight of the j^{th} indicator in the i^{th} aspect. N: number of the aspects; N_i: number of the indicators in the i^{th} aspect; $i = 1 \dots N$; $j = 1 \dots N_i$.

Note that this equal weighting is not performed by the standard AHP approach. For a better weighting process of standard AHP application, the pairwise comparison for deriving the weights is recommended if there is sufficient financial support and available relevant experts so that a more appropriate weighting process for indicators can be considered in the remaining works. In this study, from the perspective of data availability and data reliability, the equally treated weights of the sustainability aspects and of the indicators in each aspect are applied. In this special modification, once the SAs and SIs are determined, the necessary weights are derived automatically from the number of SAs and SIs. This equal-weighting process thus provides a quick view of the current groundwater status and can be applied easily to other areas.

Step 3: Data collection and SIF

Similar to the case of conventional AHP sustainability assessment application, the third step of the proposed SIF–AHP approach is to collect the actual data for evaluating the indicator values. In this study, however, we develop this step by clearly defining an SIF as an indicator to clarify the relationship between the indicator value and its sustainability index, as follows.

3.3. Defining SIF for an indicator

Normally, in the literature, sustainability indices have varied from 0 to 1 (Bui et al., 2017; Singh et al., 2007; Si et al., 2010). When the sustainability index for an aspect/indicator is 1, the 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. Clearly, the poorest sustainability level of an indicator/aspect/goal with index equal to zero means that the indicator/aspect/goal is still sustainable but that the level of sustainability is the poorest. There are no concepts of unsustainability for an economic sector, for instance, because government, enterprise, and community would do their best to make the sector's development sustainable. In this study, the sustainability indicator is defined in the way that the larger values of the indicators are, such that better contributions can be made to the sustainability aspect and goal. The final sustainability index is denoted as Ω, and the sustainability indices for aspects and indicators are denoted as Ω_A and Ω_I, respectively. An indicator is expressed as a dimensionless value (x) from 0 to 1, and Ω_I is a function of x *PleaseCheck*

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 usually used in conventional AHP applications, SIF is defined as a linear relationship between the indicator value and its sustainability index. In this case, the SIF is

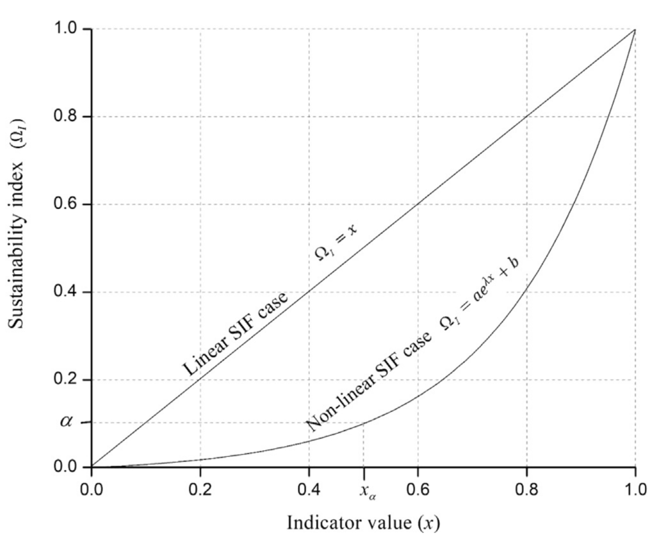

Fig. 2. Illustration of SIF based on the linear and non-linear relationships.

expressed as follows.

$$\Omega_1(x) = x \tag{5}$$

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 qualify the 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.

$$\Omega_I(x) = ae^{\lambda x} + b \tag{6}$$

where a, b and λ are coefficients.

Decision-makers need to determine the value of Ω_I at $x = x_\alpha$, which is denoted by α, satisfying the following equation.

$$\Omega_I(x_\alpha) = \alpha \tag{7}$$

The values of x_α and α depend on the specific interests of the decision-makers and differ from problem to problem. The following equations are used to determine the values of the a, b, andλ coefficients based on each specific pair of values of x_α and α.

$$a = \frac{1}{e^{\lambda}-1} \tag{8}$$

$$b = -\frac{1}{e^{\lambda}-1} \tag{9}$$

$$\alpha e^{\lambda} - \alpha - e^{\lambda x_\alpha} + 1 = 0 \tag{10}$$

Step 4: Sustainability assessment:

The sustainability index $\Omega_I(i, j)$ of the j^{th} indicator in the i^{th} aspect is evaluated based on the specific considerations for the aspects, indicators, and sustainability goal. Once all the components of the sustainability hierarchy and the SIF for indicators are determined, $\Omega_I(i, j)$ can be calculated simply according to the actual data. The sustainability index $\Omega_A(i)$ for the i^{th} aspect and the final sustainability index Ω are evaluated by using Eqs. (11) and (12), respectively.

$$\Omega_A(i) = \sum_{j=1}^{N_i} W_I(i, j) * \Omega_I(i, j) \tag{11}$$

$$\Omega = \sum_{i=1}^{N} W_A(i) * \Omega_A(i) \tag{12}$$

Therefore, naturally, the sustainability indices Ω_I, Ω_A, and Ω are within the range of 0 to 1. Additionally, these are usually categorized into several classes known as sustainability scales. In this study, we adopt the sustainability scale shown in Table 1 (Bui et al., 2016).

4. Social sustainability assessment framework for Hanoi groundwater resources

4.1. Social sustainability aspects

To identify the relevant sustainability issues, it is essential to explore the current social problems of groundwater usage and regulations in Hanoi communities carefully. In terms of social benefits, it is important to consider the social demand and satisfactory values of water

Table 1
Sustainability scale.

No.	Sustainability level	Sustainability index
1	Very poor	$0 < \Omega_I, \Omega_A, \Omega \leqslant 0.2$
2	Poor	$0.2 < \Omega_I, \Omega_A, \Omega \leqslant 0.4$
3	Acceptable	$0.4 < \Omega_I, \Omega_A, \Omega \leqslant 0.6$
4	Good	$0.6 < \Omega_I, \Omega_A, \Omega \leqslant 0.8$
5	Excellent	$0.8 < \Omega_I, \Omega_A, \Omega \leqslant 1.0$

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

Aspect	Indicator	Consideration	Index-based definition
Quantity (SA_1)	SI_{11}	Minimum water satisfactory	Ratio of residents who can use at least the Vietnamese unit water demand of 130 L/capita/day to the total population
	SI_{12}	Water restriction	One minus the ratio of residents who have suffered water restriction in a target year to the total population
	SI_{13}	24-hour water supply availability	Ratio of the average water accessed hours to 24 h in the water restriction days of the target year
Quality (SA_2)	SI_{21}	Arsenic contamination	One minus the ratio of residents who have risk of consuming the groundwater arsenic contamination to the total population
	SI_{22}	Nitrogen contamination	One minus the ratio of residents who have risk of consuming the groundwater nitrogen contamination to the total population
	SI_{23}	Coliform contamination	One minus the ratio of residents who have risk of consuming the groundwater coliform contamination to the total population
	SI_{24}	Water-related diseases	One minus the ratio of residents who have water-related diseases* to the total population
Management (SA_3)	SI_{31}	Public water coverage	Ratio of the coverage from the public water distribution network
	SI_{32}	Water work capacity	Ratio of water supply capacity to demand
	SI_{33}	Annual investment	Ratio of the annual investment in water supply per capital to the required unit costs for water supply facilities
	SI_{34}	Water affordability	One minus the ratio of the maximum water prices to the average capita income
	SI_{35}	Willingness to pay	Ratio of residents are willing to pay for improving the water supply system to the total population
	SI_{36}	Willingness to participate	Ratio of residents who are willing to participate in any water conservation and protection activities to the total population

* According to Hanoi Department of Health (HNDH, 2017), the main water-related diseases are diarrhea, skin and eye infections, Japanese encephalitis, woman gynaecological disease, basically due to a shortage of clean water use for drinking, cooking and cleaning and basic sanitation.

quantity, quality, and price. These three significant factors are controlled and driven by government management and regulations. The current problems of groundwater resources and domestic water use in Hanoi have already been presented in Sub-section 2.2 of this paper. These problems obviously have an adverse impact on the community in both the short term and the long term, which makes determining how to direct the Hanoi community toward sustainable development a challenging task for the government. A better understanding of public attitudes toward water resource management is needed, and human well-being and public support are essential for successful implementation of any water-related project and policy. Therefore, in this study, the considerations of groundwater quantity, quality, and management concepts are deemed as the three main social sustainability aspects, as shown in Table 2. It is quite difficult to judge the relative importance of each aspect that contributes to the final sustainability goal, so the main aspects in this study are given equal importance.

4.2. Social sustainability indicators for the three aspects and their index-based definitions

Regarding the development of groundwater sustainability indicators, the UNESCO/IAEA/IAH Working Group first attempted to define sustainability indicators of groundwater resources following the Driving Forces, Pressures, State, Impacts, and Societal Response (DPSIR) framework (Vrba and Lipponen, 2007). Those indicators are 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 explained how their indicator values positively or negatively affect the three specific sustainable development criteria. For groundwater quantity, for example, one indicator is defined as the ratio between groundwater extraction and recharge. Physically, this ratio can be used as a sign of groundwater overexploitation. In terms of benefits for society and economic development, the increase of groundwater extraction must be sufficient to meet the cumulative social demand. This increase, on the other hand, eventually has a series of adverse environmental and social impacts. Thus, it is apparently difficult to judge whether the increase of an indicator value contributes positively or negatively to the specific sustainability criterion. Therefore, to easily support this judgment, it is necessary to develop appropriate groundwater sustainability indicators from a particular criterion (social criterion in this case). Social sustainability indicators are context-dependent and need to reflect the nature and requirements of the local community (McKenzie, 2004), so the indicators should be selected and defined according to the current social problems related to groundwater in Hanoi.

Data are essential to develope integrated approaches for sustainable groundwater management (Rossetto et al., 2007). However, in a developing country such as Vietnam, data related to the sustainability of groundwater management are sparse, seldom organized systematically, and accessible to only a very limited number of official users even though officials have been concerned with the sustainability concept for about 10 years. In this study, we exerted much effort to gather the necessary data, and more importantly, to keep the data consistent. The primary datasets are from various sources, such as the Vietnamese government database, local and national environmental agencies, public and private research institutions, and our questionnaire survey investigations. For evaluations of the indicator values, the authorized and reliable input data that we used are from our questionnaire survey in 2014, the Ministry of Natural Resources and Environment in 2012, the Ministry of Science and Technology in 2017, and the largest water company, HAWACO, which is the government organization responsible for domestic and business water supply services in Hanoi, in 2016. In our questionnaire survey in 2014, 400 samples were collected from both urban and suburban districts in Hanoi. The purpose of the survey was to explore the public awareness about the current situation of water supply and groundwater resources, the water usage habits of the public, and the satisfaction of the public with the water quantity, quality, and management in Hanoi communities. Therefore, the input data used in these proposed indicators are reliable in the 5-year duration of 2012–2017 in Hanoi, Vietnam. Based on the criteria of data availability and reliability, low-reliability data (too old or from unpublished works) were screen out and only up-to-date, authorized, and reliable data are utilized for indicator development, as follows.

In terms of the quantity aspect (SA_1), which is a measure of the social satisfaction with water use, we consider three sustainability indicators. The first indicator of this aspect, SI_{11}, corresponds to the satisfaction of water use. As guided by the UNESCO/IAEA/IAH Working Group (Vrba and Lipponen, 2007), one indicator related to this social satisfaction is defined as the ratio of residents who use insufficient water to the total population of the targeted area. Indeed, the terms "satisfaction" and "sufficient water use" are difficult to define because water sufficiency differs from region to region and person to person,

Table 3
Social sustainability assessment for Hanoi groundwater resources.

Sustainability Aspect	$W_A(i)$	Sustainability Indicator	$W_I(i,j)$	Indicator value (x)	Linear SIF case			Combined linear & non-linear SIF case		
					Ω_I	Ω_A	Ω_I	Ω_I	Ω_A	Ω
Quantity (SA_1)	0.33	SI_{11}	0.33	0.98	0.98	0.68 (Good)	0.65 (Good)	0.98	0.68 (Good)	0.49 (Acceptable)
		SI_{12}	0.33	0.55	0.55			0.55		
		SI_{13}	0.33	0.50	0.50			0.50		
Quality (SA_2)	0.33	SI_{21}	0.25	0.44	0.44	0.66 (Good)		0.07	0.27 (Poor)	
		SI_{22}	0.25	0.57	0.57			0.14		
		SI_{23}	0.25	0.78	0.78			0.37		
		SI_{24}	0.25	0.85	0.85			0.51		
Management (SA_3)	0.33	SI_{31}	0.17	0.68	0.68	0.60 (Good)		0.68	0.52 (Acceptable)	
		SI_{32}	0.17	0.87	0.87			0.87		
		SI_{33}	0.17	0.63	0.63			0.63		
		SI_{34}	0.17	0.72	0.72			0.20		
		SI_{35}	0.17	0.56	0.56			0.56		
		SI_{36}	0.17	0.15	0.15			0.15		

depending on social needs and situation. As Vietnam is a developing country, we here define "minimum water satisfaction" as meaning people can use at least the average amount of water demanded in large Vietnamese cities (130 L/capita/day) for their basic daily activities. The second indicator of the quantity aspect (SI_{12}) represents the water restriction situation. In this study, to develop a positive correlation between indicator value and its sustainability index, SI_{12} is defined as one minus the ratio of the number of the residents who have suffered water restrictions to the total population, as described in Table 2. For the third indicator (SI_{31}), it is necessary to consider water accessibility. As defined by WHO (WHO, 2015), water accessibility is the presence of a proximal water source (within 500 m) that is available for use, without considering safety, continuity, or quantity. The issue of this general water accessibility needs to be considered in arid and semiarid regions, but it is not suitable for Hanoi because of its tropical monsoonal climate features. Thus, for SI_{13}, we consider the amount of time per day during water restriction days that the community can access water from the water supply companies, which is named "24-hour water supply availability." By these index-based definitions, the indicator values are in the range of zero to one and follows the positive correlation with their sustainability indices. The indicators of the first aspect (SA_1) and their index-based definitions are shown in Table 2.

The quality aspect (SA_2) is a measure of the social satisfaction with the water quality and degree of harm to human health. Due to the availability and reliability of the data, in this aspect, we consider only the major groundwater problems in Hanoi to develop indicators. The literature of groundwater quality in Hanoi has expressed recent concern about three major contamination agents, arsenic, nitrogen, and coliform. Thus, for the quality aspect, three indicators needed to be considered to measure how much (in percentage) of the community is at risk from each of these three contamination agents. As guided by the UNESCO/IAEA/IAH, the first indicator (SI_{21}), for example, of the quality aspect corresponds to arsenic contamination and is defined as one minus the ratio of residents at risk of consuming arsenic-contaminated groundwater to the total population. Furthermore, we consider an indicator measuring the actual health impact of the current water consumption. This fourth indicator (SI_{24}) presents water-related diseases as a macro index.

For the management aspect (SA_3), we consider how the local government manages and improves the PWSS, as the source of quality-control for the community, how the community responds to the management and water-related policies, and how ready the community is for better water use. Based on the current social situation in this study area, the first indicator (SI_{31}) refers to public water coverage. This indicator reflects the extent to which the distribution network can reach the community. The second indicator (SI_{32}) in this aspect is related to the capacity of the PWSS. This indicator refers to the balance between the water supply capacity of the PWSS and the increasing current demand resulting from the rapid urbanization in Hanoi. The third indicator (SI_{33}) presents the annual investment per capita compared to the required unit cost for water supply facilities. This indicator shows how much the government cares about the community in terms of budget allocation for PWSS development. The fourth indicator (SI_{34}) is a measure of water affordability and is defined as one minus the ratio of maximum water price to average household income. These four important indicators, SI_{31}, SI_{32}, SI_{33}, and SI_{34}, are from the point of view of government. The fifth (SI_{35}) and sixth (SI_{36}) indicators express the community response to the current water conditions and regulations, which is expressed by their willingness to pay for PWSS improvement and their willingness to participate in water-related programs, respectively.

Finally, three main sustainability aspects (quantity, quality, and management) and their three, four, and six corresponding sustainability indicators, respectively, are available to build the social sustainability hierarchy for Hanoi groundwater based mainly on current problem consideration.

5. Results and discussion

According to the index-based definitions of the indicators described in the previous section, we calculated the indicator values, which are shown in Table 3. The following sub-sections explain the procedures for obtaining the social sustainability assessment results for Hanoi groundwater from both the conventional linear 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, as shown in Eq. (5), each indicator value x is taken as its sustainability index Ω_I. The sustainability indices for Ω_A and the final social sustainability index Ω are calculated by Eqs. (11) and (12), respectively. The resulting sustainability indices are shown in the column for the linear SIF case in Table 3.

In the quantity aspect (SA_1), the indicator SI_{11} is assessed at the excellent sustainability level of 0.98 according to the sustainability scale shown in Table 1, indicating that the majority of Hanoi communities can live with the minimum water satisfaction level of 130 L/capita/day. The indicator SI_{12} is assessed at the acceptable sustainability level of 0.55, suggesting that more than half of the communities have not suffered any water restriction. Lastly, the indicator SI_{13} is also assessed at the acceptable sustainability level of 0.50, suggesting that water supply from PWSS is available for 12 h per day even when water restriction occurs. Thus, the sustainability index of the quantity aspect is assessed at a good level $\Omega_A(1)$ of 0.68. These assessment results for the quantity aspect and its indicators quite appropriately reflect the reality, because as we explored via our questionnaire survey, most of respondents agree that PWSS has been improved from a quantity perspective.

Similarly, in the quality aspect (SA_2), the SI_{21} and SI_{22} indicators regarding arsenic and nitrogen contamination are assessed at the acceptable sustainability level. SI_{23} related to coliform contamination is assessed at the good sustainability level. As a macro index, the SI_{24} indicator concerning water-related disease is assessed at the excellent sustainability level. Therefore, the sustainability index of the quality aspect is assessed at a good sustainability level of 0.66. However, from the quality point of view, as described in the study area, only half of Hanoi's population accessed PWSS, which provides quality-controlled water (HAWACO, 2014). This means that the other half is still using quality-uncontrolled water sources that could be dangerous to human health due to contamination. Additionally, the indicator SI_{21}, for example, shows that more than half (56%) of the communities are at risk of arsenic poisoning due to groundwater consumption. There are a series of publications and government reports concerning arsenic contamination of groundwater and its adverse human health impacts in Hanoi and the RRD. The government of Hanoi is trying hard to control the ever-increasing groundwater extraction 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. For a sustainable society, therefore, the sustainability index of this indicator should naturally be assessed at the very poor sustainability level. However, based on the linear SIF, the sustainability index of SI_{21} is assessed as the socially acceptable value of 0.44, which is inappropriate considering the severe arsenic groundwater pollution problems in Hanoi. Therefore, there is a gap between the social sustainability assessment and its ability to reflect the actual groundwater quality problems in Hanoi.

In the management aspect (SA_3), four of the six indicators, SI_{31}, SI_{32}, SI_{33}, and SI_{34}, are assessed at the good to excellent sustainability levels, showing that the PWSS can cover more than two-thirds of Hanoi communities and also that its capacity mostly meets the current social needs. Regarding the water investment situation, generally, Vietnam's annual investment in water supply and sanitation is less than $2 per capita per year, which is almost nothing compared to the required unit cost for water supply facilities of $113 per capita (World Bank, 2010). However, in the capital, the government of Hanoi has recently given much attention to reducing the high pressure on groundwater resources by financing a number of water treatment plants that take surface water from rivers in and near the capital. The investment indicator (SI_{33}) is thus assessed at the good level of 0.63, but it is still not sufficient to meet the communities' expectation, which is a typical condition in a developing country. To obtain the immense financial resources, large efforts should come from both government and community sectors. At the management sector, reducing the complexity of current regulations and policies and increasing opportunities for international collaboration are highly recommended to attract more external financial sources. Along with these efforts, it is also important to encourage the local communities to improve the current poor awareness of clean water and to use water efficiently. Regarding the limited public awareness of water issues, the index for SI_{36} is almost at the poorest sustainability level; most residents are not willing to participate in any water-related programs, which are intended to broaden public understanding and awareness of safe water sources. This assessment appropriately reflects the lack of awareness among the majority of local communities. However, as shown in SI_{35}, more than half (56%) of the residents in the communities desire to contribute their financial assistance to support PWSS improvement projects, which means that a majority of them would accept paying higher water prices if the PWSS can be improved. Therefore, from the linear SIF case, the sustainability index of the management aspect is at the good level of 0.60. Generally, the social sustainability index Ω_I of groundwater in Hanoi is assessed at a good sustainability level of 0.65 (Table 3).

5.2. The combined linear and non-linear SIF case

We continue to apply the linear SIF for the indicators of the quantity aspect (SA_1) because the sustainability assessment based on the linear SIF seems to appropriately reflect the current quantity situation of the water use in Hanoi.

However, in the quality aspect, as mentioned previously in subsection 5.1, the sustainability indices based on the linear SIF do not appropriately reflect the serious situation of groundwater quality problems in Hanoi. For example, regarding the risk of arsenic contamination of groundwater, if 50% ($x_\alpha = 0.5$) of the communities are at risk of contamination, the sustainability index should be assessed at some value in the very poor range levels of 0–0.2 (Table 1). Hence, this study roughly assumes the following condition (Eq. (13), such that if 50% ($x_\alpha = 0.5$) of the communities are at this risk of arsenic groundwater contamination, sustainability is assessed at the very poor value of 0.1 ($\alpha = 0.1$).

$$\Omega_1(x_\alpha = 0.5) = 0.1 \tag{13}$$

The values of α and x_α depend totally on the interests of decision-makers, which vary from situation to situation and from indicator to indicator. In order to obtain better assessment results, each indicator should be judged individually; however, like the first trial for the Hanoi case study, we also use Eq. (13) for the indicators pertaining to nitrogen contamination risk, coliform contamination risk, and the health impacts of the quality aspect (SA_2) in this study. We then obtain the following Eq. (14) for sustainability index evaluations of the four quality sustainability indicators.

$$\Omega_1(x) = 0.0125e^{4.3944x} - 0.0125 \tag{14}$$

For the management aspect (SA_3), other than the water affordability indicator SI_{34}, the assessments resulting from the linear SIF seem to be appropriate. SI_{34} is one of the interesting indicators in this aspect because it shows exactly how the government controls the price of water, which directly affects the living condition of the communities. There is actually no criterion of water affordability for any country, but we could use a suggestion from the affordability criteria of the U.S. Environmental Protection Agency (U.S. EPA), which indicates that the water bill is affordable if it constitutes less than 2.5% of the median household income. Actually, at the family and city scales, the price of the water supply somehow reaches 28% of the average monthly income (Lucía et al., 2017), $104 in Hanoi (UNDP, 2010), which is more than 10 times higher than the U.S. EPA affordability criterion. This demonstrates how difficult it is for the communities to use safe water from PWSS every single day. The safe water is physically available, but economically unattainable. So, it is necessary to apply the non-linear SIF to assess the sustainability of the water affordability indicator. The water bill reaches 28% of median income in this case, so the sustainability index should be assessed at some value in the poor range of 0.2 to 0.4, or even in the very poor range of 0–0.2. We thus roughly take the judgment from Eq. (15) of ($\alpha = 0.2$ at $x_\alpha = 0.72$) for the affordability indicator SI_{34} of the management aspect SA_3.

$$\Omega_1(x_\alpha = 0.72) = 0.2 \tag{15}$$

Using the same value x as shown in Table 3, we can obtain all the sustainability indices for all the indicators of quality and SI_{34} of the management aspect using Eqs. (13) and (15). The sustainability indices for Ω_A and the final social sustainability index Ω are then calculated correspondingly by Eqs. (11) and (12). These resulting sustainability indices are also shown in the column for the combined linear and non-linear SIF case in Table 3. The results in this case are also illustrated in Fig. 3 as a solid line in the radar chart.

From Table 3, all the sustainability indices Ω_I of the indicators of the

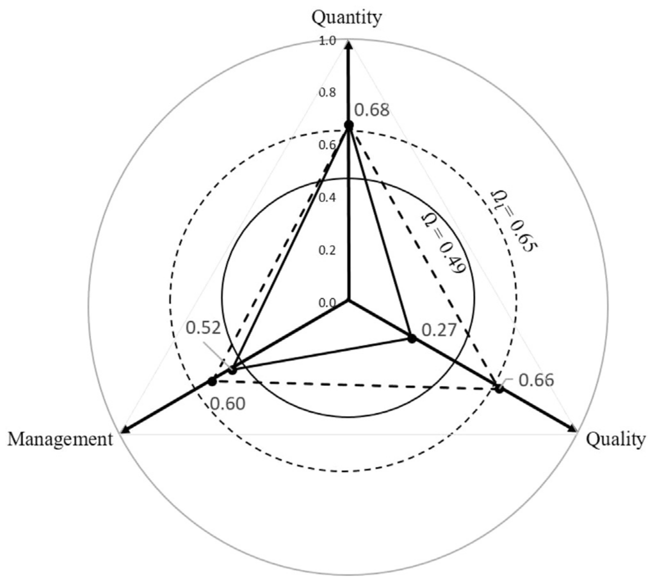

Fig. 3. Sustainability assessment visualization for groundwater resources of Hanoi (The sustainability indices for three aspects based on the linear SIF are shown as the dashed line triangle; the final social sustainability index Ω_l in this case is shown as the dashed line circle with the radius equal to Ω_l value. The sustainability indices for three aspects based on the combined linear and non-linear SIFs are shown as a solid line triangle; the final social sustainability index Ω in this case is shown as the solid line circle with the radius equal to Ω value).

quality aspect are significantly reduced compared to those based on the linear SIF. The sustainability indices of the two indicators SI_{21} and SI_{22} are reduced to the very poor sustainability level, and SI_{23} is reduced to the poor level, revealing the community's frustration with the poor quality of the groundwater in this target area. Thus, the sustainability index of the quality aspect is appropriately reduced from the good level to poor level value of 0.27. These assessment results for the quality aspect and its indicators appropriately reflect the current situation because, according to the results of our 2014 questionnaire survey, approximately one-third of Hanoi communities are dissatisfied and have complained about the water quality. There are also a series of adverse impacts on the social and environmental conditions of groundwater overexploitation and contamination (Berg et al., 2008; Bui et al., 2012b). The communities are somewhat aware of this serious situation via various media; however, due to the lack of better choices, they continue to use current water sources.

For the indicator SI_{34} of the management aspect, the sustainability index is drastically reduced to the poor level, which seems to reflect well the unbalanced condition between the average low incomes of a portion of the communities and the relatively high price of water. So, the management aspect is appropriately assessed at the acceptable sustainability level of 0.52. This assessment makes sense because, as we explored via our survey, only 6% of respondents rate the government management at a good level, and more than half of them (51%) rate it at an acceptable level.

Consequently, the final social sustainability index Ω for Hanoi groundwater is appropriately assessed at the acceptable level of 0.49 in this case (Table 3). Fig. 3 clearly illustrates the difference in the sustainability assessment results between the linear and the combined linear and non-linear SIF cases. In terms of the ability of the assessment to reflect the actual situation, the sustainability assessment results based on the combined linear and non-linear SIF are more reasonable. The final index Ω shows a socially acceptable overview of the sustainability of Hanoi groundwater resources and water supply system. It also indicates that improving the current poor quality is the key process for making a sustainable water supply much more feasible in Hanoi.

6. Conclusion

In this study, we carried out a sustainability assessment of groundwater resources from a social perspective for the first time. To accomplish this, we modified the conventional AHP approach into the SIF–AHP approach. In the SIF–AHP application for groundwater, we practically proposed 3 main aspects and their 13 core social sustainability indicators, which appropriately represent the current social groundwater situation in the capital of Vietnam. We improved the sustainability assessment by introducing the concept of SIF to clarify the relationship between indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature. The proposed sustainability framework was applied to the Hanoi case study by gathering available and reliable data to test the linear and non-linear SIF cases. We successfully assessed the sustainability of groundwater in Hanoi from a social point of view.

The results reveal that the Hanoi community is satisfied with the quantity of the groundwater but dissatisfied with its current poor quality and the relatively high prices of water. The public awareness of the insufficient water quality issue is quite poor and a lot of efforts from both the government and community are needed to move the majority of Hanoi communities out of their current state of ignorance and, more importantly, to drive Hanoi towards sustainable water supply. It is feasible that these assessments based on the combined linear and non-linear SIF were more reasonable than those of the conventional linear SIF alone because the sustainability indices properly reflected the current groundwater problems in Hanoi. Therefore, the sustainability assessment could be a more helpful baseline for any further sustainability assessments of Hanoi's groundwater. These findings are indispensable for any further sustainability assessments of groundwater resources. However, as mentioned in the methodology, Eq. (13), regarding the fixed values of α and x_α applied for the four indicators of the quality aspect, was 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 mostly limited data availability in the study area. If possible, with sufficient financial support and experts in the related fields, we could execute the more tedious process of weighting the relative contribution of each indicator by the standard AHP. Better assumptions that are applied differently for each indicator of an aspect and the more appropriate weighting process could be considered in future work.

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References

Alley, W.M., Reilly, T.E., Franke, O.L., 1999. Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186, Denver, CO.

Axelsson, R., Angelstam, P., Degerman, E., Teitelbaum, S., Andersson, K., Elbakidze, M., Drotz, M.K., 2013. Social and cultural sustainability: Criteria, indicators, verifier variables for measurement and maps for visualization to support planning. Ambio 42 (2), 215–228. http://dx.doi.org/10.1007/s13280-012-0376-0.

Berg, M., Nguyen, T.C., Pham, H.V., Schertenleib, R., Giger, W., 2001. Arsenic contamination of groundwater and drinking water in Vietnam: a human health threat. Environ. Sci. Technol. 35 (13), 2621–2626. http://dx.doi.org/10.1021/es010027y.

Berg, M., Pham, T.K.T., Stengel, C., Buschmann, J., Pham, H.V., Nguyen, V.D., Giger, W.,

Stüben, D., 2008. Hydrological and sedimentary controls leading to arsenic contamination of groundwater in the Hanoi area, Vietnam: the impact of iron-arsenic ratios, peat, river bank deposits, and excessive groundwater abstraction. Chem. Geol. 249 (1), 91–112. http://dx.doi.org/10.1016/j.chemgeo.2007.12.007.
Boggia, A., Cortina, C., 2010. Measuring sustainable development using a multi-criteria model: a case study. Environ. Manag. 91, 2301–2306. http://dx.doi.org/10.1016/j.jenvman.2010.06.009.
Brundtland, G.H., 1987. Our Common Future. Oxford University Press.
Bui, D.D., Kawamura, A., Tong, T.N., Amaguchi, H., Nakagawa, N., Iseri, Y., 2011. Identification of aquifer system in the whole Red River Delta, Vietnam. Geosci. J. 15 (3), 323–338. http://dx.doi.org/10.1007/s12303-011-0024-x.
Bui, D.D., Kawamura, A., Tong, T.N., Amaguchi, H., Trinh, T.M., 2012a. Aquifer system for potential groundwater resources in Hanoi, Vietnam. Hydrol. Process. 26 (6), 932–946. http://dx.doi.org/10.1002/hyp.8305.
Bui, D.D., Kawamura, A., Tong, T.N., Amaguchi, H., Nakagawa, N., 2012b. Spatio-temporal analysis of recent groundwater-level trends in the Red River Delta, Vietnam. Hydrogeol. J. 20 (8), 1635–1650. http://dx.doi.org/10.1007/s10040-012-0889-4.
Bui, T.N., Kawamura, A., Amaguchi, H., Bui, D.D., Truong, N.T., 2016. Environmental sustainability assessment of groundwater resources in Hanoi, Vietnam by a simple AHP approach. J. JSCE, Ser. G (Global Environmental Research) 72 (5), I137–I146. http://dx.doi.org/10.2208/jscejer.72.I_137.
Bui, T.N., Kawamura, A., Kim, K.W., Prathumratana, L., Kim, T.H., Yoon, S.H., Jang, M., Amaguchi, H., Bui, D.D., Truong, N.T., 2017. Proposal of an indicator-based sustainability assessment framework for the mining sector of APEC economies. Resour. Policy 52, 405–417. http://dx.doi.org/10.1016/j.resourpol.2017.05.005.
Chen, J., Zhang, Y., Chen, Z., Nie, Z., 2015. Improving assessment of groundwater sustainability with analytic hierarchy process and information entropy method: a case study of the Hohhot Plain, China. Environ. Earth Sci. 73, 2353–2363.
Chiu, R.L.H., 2003. Social sustainability, sustainable development and housing development: the experience of Hongkong. In: Housing and Social Change: East-West Perspectives, pp. 221–239.
Devuyst, D., Hens, L., Lannoy, W.D., 2001. How Green is the City? Sustainability Assessment and the Management of Urban Environments. Columbia University Press, New York.
Dolnicar, S., Hurlimann, A., Grun, B., 2011. What affects public acceptance of recycled and desalinated water? Water Res. 45 (2), 933–943. http://dx.doi.org/10.1016/j.watres.2010.09.030.
General Statistic Office of Vietnam, 2015. Area, Population and Population Density by Province by Cities, Provinces, Year and Items. accessed 15.11.20. http://www.gso.gov.vn/default_en.aspx?tabid=774.
HNDH (Hanoi Department of Health), 2017. Contaminated Water Sources and Health Impacts. accessed 17.10.20. http://soyte.hanoi.gov.vn/vi/news/kham-chua-benh-pho-bien-kien-thuc-y-hoc/o-nhiem-moi-truong-va-mot-so-van-de-ve-suc-khoe-1474.html.
HAWACO, Hanoi Water Limited Company, 2014. Hanoi water supply system. Unpublished work. PowerPoint presentation viewed as part of the guided visit to HAWACO's Hoa Binh WTP during the 37th WEDC international Conference: Sustainable water and sanitation services for all in a Fast changing world, co-hosted by Loughborough university and the national university of civil engineering (NUCE), 15-19 September 2014 (Date of guided visit: 18 September 2014).
HAWACO, Hanoi Water Limited Company, 2016. Temporary Water Shut-off Schedule. accessed 16.10.20. http://hawacom.vn/?cat=67.
Hutton, G., Bartram, J., 2008. Regional and global costs of attaining the water supply and sanitation target (Target 10) of the Millennium Development Goals. World Health Organization, Geneva.
Li, P., Qian, H., Howard, K.W.F., Wu, J., 2015. Building a new and sustainable "Silk Road economic belt". Environ. Earth Sci. 74 (10), 7267–7270. http://dx.doi.org/10.1007/s12665-015-4739-2.
Li, P., Tian, R., Xue, C., Wu, J., 2017. Progress, opportunities and key fields for groundwater quality research under the impacts of human activities in China with a special focus on western China. Environ. Sci. Pollut. R. 24 (15), 13224–13234. http://dx.doi.org/10.1007/s11356-017-8753-7.
Lucía, W.C., March, H., Schramm, S., 2017. Fragmented landscapes of water supply in suburban Hanoi. Habitat Int. 61, 64–74. http://dx.doi.org/10.1016/j.habitatint.2017.02.002.
Mani, V., Agarwal, R., Gunasekaran, A., Papadopoulos, T., Dubey, R., Childe, J.S., 2016. Social sustainability in the supply chain: Construct development and measurement validation. Ecol. Indic. 71, 270–279. http://dx.doi.org/10.1016/j.ecolind.2016.07.007.
McKenzie, S., 2004. Social Sustainability, Towards Some Definitions. University of South Australia.
Mende, A., Astorga, A., Neumann, D., 2007. Strategy for groundwater management in developing countries: a case study in northern Costa Rica. J. Hydrol. 334 (1–2), 109–124. http://dx.doi.org/10.1016/j.jhydrol.2006.10.016.
Ness, B., Piirsalu, E.U., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508. http://dx.doi.org/10.1016/j.ecolecon.2006.07.023.
Nguyen, T.T., Kawamura, A., Tong, T.N., Nakagawa, N., Amaguchi, H., Gilbuena, R., 2014. Hydrogeochemical characteristics of groundwater from the two main aquifers in the Red River Delta, Vietnam. J. Asian Earth Sci. 93, 180–192. http://dx.doi.org/10.1016/j.jseaes.2014.07.035.
Nguyen, T.T., Kawamura, A., Tong, T.N., Nakagawa, N., Amaguchi, H., Gilbuena, R., Bui, D.D., 2015a. Identification of spatio-seasonal hydrogeochemical characteristics of the unconfined groundwater in the Red River Delta, Vietnam. Appl. Geochem. 63, 10–21. http://dx.doi.org/10.1016/j.apgeochem.2015.07.009.
Nguyen, T.T., Kawamura, A., Tong, T.N., Nakagawa, N., Amaguchi, H., Gilbuena, R., 2015b. Hydrogeochemical assessment of groundwater quality during dry and rainy seasons for the two main aquifers in Hanoi, Vietnam. Environ. Earth Sci. 73, 4287–4303. http://dx.doi.org/10.1007/s12665-014-3713-8.
Nguyen, T.T., Kawamura, A., Tong, T.N., Nakagawa, N., Amaguchi, H., Gilbuena, R., 2015c. Clustering spatio-seasonal hydrogeochemical data using self-organizing maps for groundwater quality assessment in the Red River Delta, Vietnam. J. Hydrol. 55, 661–673. http://dx.doi.org/10.1016/j.jhydrol.2015.01.023.
Plate, E.J., 1993. Sustainable development of water resources: a challenge to science and engineering. Water Int. 18 (2), 84–94. http://dx.doi.org/10.1080/02508069308686154.
Pinar, M., Cruciani, C., Giove, S., Sostero, M., 2014. Constructing the FEEM sustainability index: a Choquet integral application. Ecol. Indic. 39, 189–202. http://dx.doi.org/10.1016/j.ecolind.2013.12.012.
Rossetto, R., Baldi, B., Perna, M., Carmignani, L., 2007. Use of GIS hydrogeological database for integrated water management. In: Geophysical Research Abstracts. European Geosciences Union, pp. 92–94.
Saaty, T.L., 2000. Fundamentals of Decision Making and Priority Theory. RWS Publications, PA, Pittsburgh.
Si, H., Bi, H., Li, X., Yang, C., 2010. Environmental evaluation for sustainable development of coal mining in Qijiang, Western China. Int. J. of Coal Geol. 81 (3), 163–168. http://dx.doi.org/10.1016/j.coal.2009.11.004.
Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2007. Development of composite sustainability performance index for steel industry. Ecol. Indic. 7 (3), 565–588. http://dx.doi.org/10.1016/j.ecolind.2006.06.004.
Sun, S., Wang, Y., Liu, J., Cai, H., Wu, P., Geng, Q., Xu, L., 2016. Sustainability assessment of regional water resources under the DPSIR framework. J. Hydrol. 532, 140–148.
United Nations, 2015. Water for a sustainable world, facts and figures. The United Nations World Water Development Report.
United Nations, 2017. Sustainable Development Goals. accessed 17.11.20. http://www.undp.org/content/undp/en/home/sustainable-development-goals.html.
UNDP, 2010. Urban Poverty Assessment in Hanoi and Ho Chi Minh City. Accessed: 14 September 2017. http://www.vn.undp.org/content/vietnam/en/home/library/poverty/urban-poverty-assessment-in-ha-noi-and-ho-chi-minh-city.html.
Vallance, S., Perkins, H.C., Dixon, J.E., 2011. What is social sustainability? A clarification of concepts. Geoforum 42 (3), 342–348. http://dx.doi.org/10.1016/j.geoforum.2011.01.002.
Vrba, J., Lipponen, A., 2007. Groundwater resources sustainability indicators, IHP-Viseries on Groundwater, No. 14.
VUFO-NGO Resource Centre, 2017. Diseases in Vietnam Caused by Polluted Water Resources. accessed 17.01.20. http://www.ngocentre.org.vn/content/80-diseases-vietnam-caused-polluted-water-resources.
WHO (World Health Organization), 2015. Water, sanitation and hygiene (WASH) in health-care facilities. World Health Organization, Geneva http://apps.who.int/iris/bitstream/10665/154588/1/9789241508476_eng.pdf (accessed 17.10.10).
World Bank, 2010. Project Paper on a Proposed Additional Financing Credit in the Amount of SDR 42 million to the Socialist Republic of Vietnam for the River Delta Rural Water Supply and Sanitation Project, March 2010.
Yu, C.S., 2002. AGP-AHP method for solving group decision- making fuzzy AHP problems. Comput. Oper. Res. 29, 1969–2001.