BASIC STUDY ON SUSTAINABILITY ASSESSMEENT OF GROUNDWATER RESOURCES IN HANOI, VIETNAM

By

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A dissertation submitted in partial fulfillment of the requirements for the Degree of Doctor of Engineering in Civil and Environmental Engineering, with specialization in Urban Environmental Hydrology

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Basic Study on Sustainability Assessment of Groundwater Resources in Hanoi, Vietnam

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DEDICATIONS

To my ever supportive better half,

my kind father, Bố Minh Thành and my lovely mommy, Mẹ Hiệt

To my kind husband, Anh Ngọc Tú

To my little princess, con gái Merci Ngân Bảo-chan

To my loving Family and my Family in-law

And to all my colleagues and friends in TMU who have made my life as a

Ph.D. student a lot more worthwhile

You've guided me through, encouraged my efforts, endured and shared my failures, applauded my successes, and patiently waited for the culmination of this work,

I am forever thankful.

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PREFACE

This dissertation is accomplished as partial fulfillment of my requirements in the doctoral course in engineering at the Hydrology and Water Resources Laboratory of the Department of Civil and Environmental Engineering, Graduate school of Urban Environmental Sciences, Tokyo Metropolitan University from Oct. 2015 to Sept. 2018 under the supervision of Professor Akira Kawamura. The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

The content in this dissertation is based on 8 scientific articles which have been reviewed and refereed in the international journals; most parts have been presented in a number of domestic and international conferences. This thesis mainly focuses on a basic study of sustainability assessment of groundwater resources in Hanoi, Vietnam. For the first time, Multi-criterial decision making approach is utilized to generate main sustainability criteria, aspects and core indicators, which present the overall situation of environmental, social and economic performances of groundwater development. The obtained results from this study are indispensable for ensuring sustainable development of groundwater resources in Hanoi, Vietnam.

This study was carried out as a part of the research project "Study on guerrilla rainstorms, flood inundation and water pollution in metropolitan watersheds" supported by the Tokyo Metropolitan Government, Japan (represented by A. Kawamura) within the program "Tokyo Human Resources Fund for City Diplomacy Scholarship 2015". We would like to thank Ministry of Natural Resources and Environment of Vietnam for supplying the necessary field data from the earlier feasibility studies.

Tokyo Metropolitan University, Tokyo, Japan.

September 10, 2018

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My deepest gratitude goes to my family for their unflagging love and support throughout my life; this thesis is simply impossible without them. I am grateful to my father Bui Minh Thanh and my mother Bui Thi Hiet for their care and endless love. As a typical mother in a Vietnamese family, she is so gracious and intelligent; she has worked so hard to support to my big family and spare no effort to provide the best possible environment for me to grow up. I have no suitable word that can fully describe her everlasting love to me. She supports me the motivations to go further confidently because she is always proud of me. Her love is incredible to help me try my best to be happy at any situation. While my father is no longer with me, but I know that he is always watching me and his love grew me up, I respectfully miss him until the end of my life. Mom and Dad, I miss you now and I love you both very much more than you can imagine.

My deepest gratitude also goes to my whole family, especially to my husband, my brothers and sisters, my in-laws and my nephews, for their genuine emotional care, unconditional love and support. Even from a distance, they were able to provide me the best possible condition that allowed me to persevere in my study abroad. It is also my heartfelt thanks to my little princess, Mss. Truong Gia Ngan Bao (Merci-chan). Merci-chan always besides me and shares with me any happy and/or sad moment. Her simple love strengthens my mind and encourages me to be a powerful woman who could overcome any difficulty for entire of my life.

Last but not the least, many thanks to all my dear friends and colleagues from the Vietnamese community in Tokyo and to all of my friends from various nations, both inside and outside the Tokyo Metropolitan University, for their unrelenting support and encouragements.

The acknowledgement is perhaps the only part that will be read by anyone looking into this thesis. Therefore, I sincerely hope I did not forget someone. I am the only one to blame if so.

Even though I will leave Tokyo Metropolitan University this coming October, my student life here is unforgettable. One day, I will be back to just say "*Konichiwa*".

My deepest thanks,

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ABSTRACT

Groundwater plays a key role in public water supplies around the world. In Hanoi, Vietnam, the communities mainly depend on the groundwater for domestic, industrial and commercial purposes. The rapid groundwater exploitation without an adequate institutionalized management system has caused a series of adverse impacts such as drying up of shallow wells, decline of groundwater level, land subsidence and groundwater pollution. There have been a number of Hanoi-targeted studies regarding groundwater potential investigation, groundwater level trends and groundwater quality with the prevalence of severe arsenic contamination. However, none of them have dealt with sustainability assessment of groundwater resources as a primary objective and how to translate this objective into a set of more specific actions, which could provide a sufficient information to assist decision-making effectively. To this end, sustainability assessment is considered as a useful technique in any application field specifically in sustainable water resources development. This technique can provide a certain level of awareness on the environmental, social and economic benefits, which is necessary to support the preservation of this resource for future generations.

Regarding sustainability assessment methodologies, Multi-Criteria Decision Making (MCDM) methods have been considered as a proper approach for sustainability assessment. Analytical Hierarchy Process (AHP) is one of the most popular and powerful MCDM methods due to its ability to cope with multifaceted and unstructured problems such as environment, economic and social sustainability. The main advantage of AHP applications for sustainability assessment is their capability to categorize and identify the main components (criteria, aspects and indicators) that better reflect significant performances. An indicator-based AHP is common for sustainability assessment but it has been not intensively investigated for groundwater yet. Therefore, a study dealing with the indicator-based AHP sustainability assessment of groundwater is necessary to provide fundamental references for finding solutions towards sustainability of the resource.

Based on these above-mentioned reasons, this dissertation focuses on the following main objectives: (i) to develop an indicator-based AHP for sustainability assessment of groundwater resources (AHP-SAG) to cope with the limited data availability and reliability, and insufficient financial supports in the developing countries like Vietnam; (ii) to develop a clearly defined sustainability assessment framework including the utmost sustainability goal, associate with its sustainability criteria, aspects and indicators for groundwater resources of Hanoi by using the proposed AHP-SAG; (iii) to apply the proposed AHP-SAG framework for a reasonable sustainability assessment of groundwater resources in Hanoi.

In order to achieve these main objectives, this dissertation is composed of five chapters:

Chapter 1 was comprised of the background, motivation, and objectives of this study. A comprehensive review of literature and a description of the scopes and methods were presented.

Chapter 2 focused on current sustainability issues of groundwater resources in Hanoi, Vietnam. A brief description of the basic topographical conditions, current situation of domestic water uses, and groundwater conditions of Hanoi was provided. The environmental and socioeconomic sustainability issues of groundwater in Hanoi were comprehensively reviewed and presented.

Chapter 3 proposed a sustainability assessment framework for groundwater resources, which was mainly developed from the AHP. In the proposed AHP-SAG, weighting process, the most tedious step in the conventional AHP applications was modified to make it simple. A necessary concept of sustainability index function (SIF) was introduced to make a clear relationship between an indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature. In sustainability assessment studies, a reasonable assessment is the one whose results could reflect appropriately the actual situation in reality. So in this Chapter, not only the linear SIF, which was usually carried out in the conventional AHP application for sustainability assessment, but also the non-linear SIF cases were also investigated to find out a reasonable sustainability assessment for groundwater resources. The proposed AHP-SAG approach is described in detail in this Chapter.

Chapter 4 dealt with the applications of the proposed AHP-SAG technique in sustainability assessment of groundwater resources in Hanoi, in which all the three main pillars (environmental, social and economic) of sustainability concept were considered as the three important sustainability criteria in the framework. Based on the available and reliable data of the current groundwater situation in the target area, the sustainability aspects were proposed as quantity, quality, and management in each criterion. Furthermore, the sustainability indicators in each aspect were defined clearly, which could present the overall situation of groundwater resources development in Hanoi.

For sustainability assessment, the environmental, social and economic criteria were composed of their twelve, thirteen and nine (34 in total) core sustainability indicators, respectively. By gathering the necessary data, environmental, social and economic sustainability assessment of Hanoi was investigated by using the proposed AHP-SAG. It was found that the sustainability indices assessed by the combined linear and non-linear SIF case were more reasonable than the conventional linear SIF alone because the sustainability indices properly reflected the current groundwater problems in Hanoi. The environmental, social and economic criteria were appropriately assessed at acceptable, acceptable, and good sustainability levels, respectively. Lastly, the final sustainability index was assessed at acceptable level. However, there was a big variation among the 34 sustainability index values of indicators. Some indicators were assessed closely to the poorest but the others were even reaching the most excellent sustainability levels. The variability of the environmental sustainability indices indicated that the current groundwater abstraction networks are heavily concentrated to some specific areas in Hanoi, which is not successful to utilize the rich recharge from nature. From the social viewpoint, the communities are satisfied with the quantity but dissatisfied with the current poor quality and the relative high water prices. Some economic sustainability indices revealed that there was a considerable economic loss due to the ineffective water supply in the target area. The proposed AHP-SAG method thus provided a clear panoramic view of the environmental, social and economic impacts on sustainability of groundwater resources in Hanoi.

Chapter 5 presented the overall conclusions and recommendations for sustainable groundwater resources management in Hanoi, including the future research works.

PUBLICATIONS

This dissertation is mainly formulated based on eight scientific articles as the main milestones of the study which were reviewed and assessed by globally refereed journals. In addition, the some parts of this work have been presented in a number of domestic journals and international conferences. The following list presents the publications which are either published, accepted, or under review. (* means that the content of the paper connect directly to this dissertation.)

Journal Publications

1*. Bui, T. N., Kawamura, A., Bui, D. D., Amaguchi, H., Bui, D. D., Truong, N. T., Do, T. H. H., Nguyen, T. C., 2018a. Groundwater Sustainability Assessment Framework: A Demonstration of Environmental Sustainability Index for Hanoi, Vietnam. Journal of Environmental Management (Under revision).

2*. Bui, T. N., Kawamura, A., Amaguchi, H., Bui, D. D., Truong, N. T., Nakagawa, K., 2018b. Social Sustainability Assessment of Groundwater Resources : A case study of Hanoi, Vietnam. Ecological Indicators 93, pp. 1034-1042.

3*. Bui, T. N., A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, N. H. Nguyen, 2018. Sustainability Assessment Framework for Groundwater Resources in Hanoi, Vietnam from an Economic Perspective. Innovative Water Solutions for Vietnam and Region, pp. 82-93.

4. T. T. H. Nguyen, M. Takeshi, N. T. Bui, 2018. Seasonal Variation of Net Ecosystem Exchange and Energy Fluxes in Okayama Barley Field in Japan. Innovative Water Solutions for Vietnam and Region, pp. 23-37.

5. D. D. Bui, H. A. Nguyen, T. T. L. Du, B. Joost, N. T. Bui, T. T. Nguyen, V. T. Don, V. N. Le, T. T. P. Bui, 2018. Water allocation in trans-boundary river basin during

droughts: A case study of Vu Gia Thu Bon Basin, Vietnam. Innovative Water Solutions for Vietnam and Region. pp. 57-73.

6*. Bui, T. N., Kawamura, A., Amaguchi, H., Bui, D. D., Truong, N. T., Nguyen, H. N., 2017. Economic Sustainability Assessment of Groundwater Resources: A Case Study of Hanoi, Vietnam. Journal of Environmental Sciences and Engineering, Vol(B6) 12, pp.624-33. DOI:10.17265/2162-5263/2017.12.003.

7*. Bui, N. T., Kawamura, A., Amaguchi, H., Bui, D. D. and Truong, N. T., 2017. Social Sustainability Assessment of Groundwater Resources in Hanoi, Vietnam by a simple AHP Approach. Towards Sustainable Cities in Asia and the Middle East, pp.79-97. DOI: 10.1007/978-3-319-61645-2_7.

8*. Bui, T. N., Kawamura, A., Amaguchi, H., Bui, D. D., Truong, N. T., Nakagawa, K., 2017. Sustainability Assessment of Groundwater Resources in Hanoi, Vietnam from a Social Perspective. J.JSCE, Ser. G. (Environmental Research), Vol.73, No.5, pp.I_17- I_24.

9*. N. T. Bui, A. Kawamura, K.W. Kim, L. Prathumratana, T. H. Kim, S. H. Yoon, M. Jang, H. Amaguchi, D. D. Bui and N.T. Truong, 2017. Proposal of an Indicator-based Sustainability Assessment Framework for The Mining Sector of APEC Economies. Resources Policy, Vol.52, pp.405-417. DOI: 10.1016/j.resourpol.2017.05.005.

10. Duong D. Bui, Nguyen C. Nghia, Nuong T. Bui, Anh T. T. Le, Dao T. Le, 2017. Climate Change and Groundwater Resources in Mekong Delta, Vietnam. Journal of Groundwater Science and Engineering, Vol.5, No.1, pp.76-90.

11*.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. (Environmental Research), Vol.72, No.5, pp. I_137-I_146. DOI: 10.2208/jscejer.72.I_137.

12. N. T. Bui, K. W. Kim, L. Prathumratana, K. Y. Lee, T. H. Kim, S. H. Yoon, M. Jang, D. D. Bui, 2011. Sustainable development in the mining sector and its evaluation

using Fuzzy AHP (Analytic Hierarchy Process) approach. Journal of Geosystem Engineering, No. 14(1), pp. 43-50. DOI: 10.1080/12269328.2011.10541329.

International Conference Publications

1*. N. T. Bui, A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, H. N. Nguyen, 2018. Eco-social Sustainability Assessment of Groundwater Resources in Hanoi, Vietnam. Proceedings of the Resources for Future Generations. Vancouver, BC, CANADA, June 15-21, p.199.

2. N. T. Truong, N. T. Bui, B. Rao, F. M. Bai, Y. L. Shen, 2018. D-Lactic Acid Microbial Production by *Serratia marcescens* MG113: Investigation of Fermentation Parameters and Fed-Batch Strategies. Proceedings of the Resources for Future Generations. Vancouver, BC, CANADA, June 15-23, p. 210.

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4*. N. T. Bui, A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, 2017. Assessment of the disastrous groundwater resources in Hanoi, Vietnam from an environmental perspective. The 14th Annual Meeting Asia Oceania Geosciences Society. Singapore, August 6-11, USB.

5. N. H. Tran, T. T. L. Du, H. T. Do, M. T. N. Hoang, N. T. Bui and D. D. Bui, 2017. Assessing Effectiveness of Traditional Ecological Knowledge for Reducing Urban Flood Risks in Hanoi, Vietnam. Proceedings of the 14th Annual Meeting Asia Oceania Geosciences Society. Singapore, August 6-11, USB.

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Sustainability Indicators of Groundwater Resources of Hanoi, Vietnam. Proc. of the 5th International Symposium & Exhibition, Managing Transboundary Waters: From Policy to Practice. Hanoi, Vietnam, October 3-4, pp.187-195.

7*. N. T. Bui, A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, 2016a. Sustainability Assessment of Groundwater Abstraction in Hanoi, Vietnam. Proc. Of The 7th International Conference on Water Resources and Environment Research (ICWRER2016). Kyoto, Japan, June 5-9, pp. g14-10-1-g14-10-6.

8. Bui, N. T., Kawamura, A., Kim, K. W., Prathumratana, L., Amaguchi, H., Bui, D. D. and Truong, N. T., 2016b. Sustainable Development Evaluation for Mining Sectors in Japan and Vietnam. Proc. of the World Environmental and Water Resources Congress 2016, ASCE, Florida, USA, May, pp. 174-183.

9. N. T. Bui, K. W. Kim, L. Prathumratana, A. Lee, K.Y. Lee, T. H. Kim, S. H. Yoon, M. Jang and D. D. Bui, 2010. Fuzzy Analytic Hierarchy Process in evaluation of Sustainable development for Vietnam's mining sector, 2010 APEC international workshop on "Balancing competing demands of mining community and environment to achieve sustainable development in mining sector", Seoul, South Korea, September, 2010.

10. N. T. Bui, K. W. Kim, S. Suthipong, D. D. Bui, 2010. Prevalence of arsenic in groundwater resources in Hanoi 2, Vietnam. Proceedings of SEGH 2010 International Conference on Environmental Quality and Human Health, Galway, Ireland, June 2010, pp. 51-52.

11. N. T. Bui, K. W. Kim, L. Prathumratana, A. Lee, K. Y. Lee, T. H. Kim, S. H. Yoon, M. Jang and D. D. Bui, 2010. Capability of fuzzy AHP by selecting water resources plan under drought conditions in Mekong River Basin, the 8th UNU & GIST Joint Programme Symposium: 'Environmental Issues of the Mekong River', Gwangju, South Korea, November, 2010.

12. D. D. Bui, H. A. Hoang, N. T. Bui, H. T. Do, D. D. Bui, H. T. Dang. 2010.

Watershed modeling for assessment of water quality of the Sesan basin, Vietnam. Proceedings of 5th Vietnamese -Japanese Students' Scientific Exchange Conference, Tokyo, Japan, October, 2009, pp.150-151.

13. D. D. Bui, C. M. Vu, T. N. Tong, N. T. Bui, H. Do, 2008. Application of 3D numerical modeling for assessing and forecasting saltwater intrusion into groundwater at the Red River plain, Vietnam. Proceedings of 4th Vietnamese -Japanese Students' Scientific Exchange Conference, Kyoto, Japan. November, 2008, pp.245-246.

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Domestic Conference Publications

1*. 下崎 仁大, 河村　明, 天口英雄, N. T. Bui, 2018. ベトナム・ハノイ市における社会的評価基準による地下水持続可能性評価. 第 45 回土木学会関東支部研究発表会講演集, March 2018, CD-ROM: VII-22.

2*. 下崎 仁大, 河村　明, 天口英雄, N. T. Bui, 2017. ベトナム・ハノイにおける地下水資源の環境持続可能性評価について第 44 回土木学会関東支部研究発表会講演集, March 2017, CD-ROM: VII-41.

3*. N. T. Bui, A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, 2016. Social sustainability assessment framework for groundwater in Hanoi, Vietnam by AHP approach. Proceedings of 2016 Annual Conference, Japan Society of Hydrology and Water Resources, pp. 54-55.

4*. N. T. Bui, A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, 2016. Current situation of groundwater abstraction in Hanoi, Vietnam from the viewpoint of sustainability. 2015 Kanto Branch of Japan Society of Civil Engineers and Tokyo City University (第 43 回土木学会関東支部技術研究発表会), VII-12.

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LIST OF ABBREVIATIONS

RRD	Red River Delta, Vietnam
HUA	Holocene unconfined aquifer
PCA	Pleistocene confined aquifer
NAWAPI	National Center for Water Resources Planning and Investigation
HAWACO	Hanoi Water Limited Company
HSDC	Hanoi Sewerage and Drainage Limited Company
MONRE	Ministry of Natural Resources and Environment, Vietnam
UNDP	United Nations Development Programme
WHO	World Health Organization
AHP	Analytical Hierarchy Process
AHP-SAG	Analytical Hierarchy Process- Sustainability Assessment framework for Groundwater
MCDM	Multicriteria Decision Making
GSC	Groundwater Sustainability Criteria
GSA	Groundwater Sustainability Aspect
GSI	Groundwater Sustainability Indicator
EST	Environmental Sustainability Threshold
SIF	Sustainability index function
ESI	Environmental Sustainability Index

SSI	Social Sustainability Index
CSI	Economic Sustainability Index
All-purpose GSI	All-purpose Groundwater Sustainability Index

LIST OF SYMBOLS

$W_C(i)$	The weight of the i^{th} criterion
$W_A(i, j)$	The weight of the j^{th} aspect in the i^{th} criterion
$W_I(i, j, k)$	The weight of the k^{th} indicator in the j^{th} aspect of the i^{th} criterion
N	Number of the criteria
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
x	Indicator value
Ω	All-purpose groundwater sustainability index
$\Omega_C(i)$	Sustainability indices for the i^{th} criterion
$\Omega_A(i, j)$	Sustainability indices for the j^{th} aspect of the i^{th} criterion
$\Omega_I(i, j, k)$	Sustainability indices for the k^{th} indicator in the j^{th} aspect of the i^{th} criterion
a, b and λ	Coefficients

CHAPTER 1

INTRODUCTION

1.1. Background and motivation

1.1.1 Sustainable development concept

The term "sustainable" has been used in various situations nowadays. It might be mentioned as sustainable development, sustainable growth, sustainable economies, sustainable societies, and sustainable agriculture (Temple, 1992). Everything requires being sustainable and sustainable development issues become urgent global tasks for humankind.

There have been a series of sustainability views existing in literature and depending on the specific application fields. In agriculture, for example, sustainability is considered as a property, the ability of an agroecosystem to maintain productivity when subjected to a major disturbing force (Conway, 1987). Sustainability is as a goal of policy development at the global, national and local levels. Sustainability is as a value, living in harmony with one's environment, doing no harm, protecting the environment, and saving the world. Sustainability is an action, such as recycling, composting, reducing energy use, developing biofuels, producing organic foods, and minimizing one's environmental footprint. Another consideration is that sustainability is a science, providing a framework for systematic understanding of the interactions between human and environmental systems (Clark, 2007). Therefore, it is quite difficult to find a common definition of sustainable development among all sectors in eco-sociological activities.

The appropriate term of sustainability is normally considered as a process that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Sustainable development term has been determined by United Nations World Commission on Environment and Development in 1987, in the report of "*Our Common Future*", also called "*The Brundtland Report*". This definition has been released and applied to achieving development while preserving the environment by the Brundtland Commission. This report has been published in six languages after a year of visiting capitals of major world economies studying their economic, social and environmental situation. The term of sustainable development has been applied for summing the conditions to help humankind to avoid crises which have been impending since the end of the 20^{th} century.

The concept of sustainable development has become one of global critical issues for more than two decades. Economic development for better lives is a main goal of economic activities, but how to not make those activities harmful to our social and environmental condition is also extremely important for sustainable development. Every year, there are a number of publications in regard to sustainable development issues for a wide range of socio-economic sectors in the developed countries. There are a number of such examples of *The Concept of Sustainable Economic Development* (Barbier et al., 1987), *Blueprint for a Green Economy* (Barbier et al., 1989), *Sustainability Constraints versus 'Optimality' versus Intertemporal Concern, and Axioms versus Data* (Pezzey, 1997), *Economic Analysis of Sustainability* (Asheim, 1999*), Sustainable Growth Renewable Resources, and Pollution* (Le Kama, 2001), *Sustainable Development: Why The Focus on Population?* (Aguirre, 2002), *The Case for Strong Sustainability* (Ott, 2003), *The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century* (Adams, 2006), *Dimensions of Sustainability* (Hasna, 2007), *Climate Economics: A Meta-Review and Some Suggestions for Future Research* (Heal, 2009), etc. Those studies are mainly investigated in the developed countries, however, it is apparently difficult to bring the researches which have been done in the developed countries to apply directly for the cases of the developing ones. Even though, the developing countries recently have gradually incorporated this concept in their development strategies; they normally have faced a number of difficulties of lack of sufficient financial sources, relevant experts, appropriate methods, professional management systems, and even poor public awareness. Therefore, it is essential to carry out such sustainable development and sustainability studies for the developing countries which are so much difficult nowadays.

1.1.2 Sustainability assessment

Described by Moles et al. (2008), sustainability is "*an inspirational future situation*" and sustainable development is "*the process by which we move from the present status quo towards this future situation*". There have been a number of researches regarding evaluation of individual sustainability criterion of environmental, social and economic performances.

Regarding environmental sustainability assessment, there were some studies including pilot environmental performance index (WEF, 2002), index of environmental friendliness (Statistics Finland, 2003), eco-indicator 99 (Pre Consultants, 2004). For example, World Economic Forum had constructed a pilot environmental performance index (EPI) designed to measure current environmental results at national scale (WEF, 2002). The EPI was derived from a collection of data sets aggregated into four core indicators that gauge air and water quality, greenhouse gas emissions, and land protection. They provided measures of both current performance and rates of change of these indicators. The results-oriented EPI provided a valuable counterpoint to their environmental sustainability index (ESI), which covered a much broad range of conditions aimed at measuring long-term environmental prospects. However, to comprehensively measure the environmental sustainability, we need to consider more the important contributions of economic and social development factors. The main reasons are explained as follows. On the one hand, the more development the economy could be, the better funding sources it could provide for environment protection projects. On the other hand, because people are the main factors of any eco-social activities, if they have better awareness of environment protection, the negative impacts could be able to reduce from their activities.

Regarding economic sustainability assessment, some researchers have been interested in internal market index (JRC, 2002), composite leading indicators (OECD, 2002), index of sustainable and economic welfare (Daly and Cobb, 1989), etc. For example, the OECD (2002) has designed the composite leading indicators (CLIs) to provide early signals of turning points (peaks and troughs) between expansions and slowdowns of economic activities. CLIs have been calculated by combining a wide range of key short-term economic indicators such as observations or opinions about economic activity, housing permits granted financial and monetary data, labor market statistics, information on production, stocks and orders, foreign trade, etc. CLIs provide an important aid for short-term forecasts (6-12 months) of changes in direction of the economy. However, CLIs are instruments of analysis without substitutes for quantitative or long-term forecasts based on econometric models (OECD, 2002).

Regarding social sustainability assessment, human development index (UNDP, 1990–2003) and overall health system attainment (Murray et al., 2001) have been studied for this evaluation. For example, the human development index (HDI) is a summary measure of human development. The HDI measures the average achievement in a country in three basic dimensions of human development including 1) a long and healthy life, as measured by life expectancy at birth; 2) knowledge, as measured by the adult literacy rate and the combined primary, secondary and tertiary gross enrolment ratio; and 3) a decent standard of living, as measured by GDP per capita.

Therefore, an integrated sustainability assessment approach is required to ensure a balanced development among three main sustainable development pillars of economic, environmental and social sustainability performances, which requires many factors or criteria to be considered for evaluation.

1.1.3 Sustainable groundwater resources assessment as a key process in sustainable urban development

The proper management of water resources is crucial for ensuring sustainable socio-economic 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). Surface water and groundwater are two main water sources worldwide. Generally, groundwater quality is higher, well protected from surface contaminants, less susceptible to drought, and much more uniformly spread over large regions than surface water. Groundwater plays a key role in water supplies worldwide (Nguyen, 2014). More than two billion people depend on groundwater for their daily water supply, and over half of the global population depends on it for drinking (United Nations, 2015). For instance, in Denmark, Malta, Saudi Arabia, groundwater is the unique water supply source; in Tunisia, groundwater is 95% of the country total water resources, this proportion is 83% in Belgium, 75% in the Netherlands, Germany and Morocco (Igor and Lorne, 2004). The use of groundwater as a source for drinking water has expanded much in recent years and today makes up to 30% of the total water extraction of the world (Younger, 2007). Based on Jury and Vaux (2005), global population will increase by three billion or more over the next 50-75 years, and the number of people living in urban areas will be more than double. Consequently, groundwater withdrawals will be continuously rising due to the ever-increasing of the human population globally. Therefore, achieving sustainable groundwater management is one of the essential objectives for the future of many countries (Mende et al., 2007).

Regarding sustainable groundwater development (SGD), there has been much effort to define and describe this concept into a clear understanding. Focusing on social demand and water supply market, Plate (1993) defines that sustainable groundwater development means a sufficient quantity and quality of groundwater at an acceptable price which is available to meet social demands of the region without causing any environmental degradation. In this definition, environmental degradation (etc. declined groundwater level trend, land subsidence, groundwater pollution, and saline water intrusion in coastal areas) is the only consequence considered. More emphasized on the environmental degradation point of view, another research presents the key principles of SGD, which includes long-term conservation of groundwater resources, protection of its quality from significant degradation and consideration of environmental impacts of groundwater development (Gupta and Onta, 1997). Environmental degradation is not only thing needed to be considered as a certain consequence of groundwater misuse manner, however, social and economic impacts (etc. human health problems, increasing water price due to expensive pumping setting cost) are also important aspects because these impacts directly/indirectly affect to SGD. After that, other descriptions of SGD have been described in a more suitable way; SGD refers to the way of developing and using groundwater, in which the resource can be preserved for an indefinite time without causing any adverse eco-environmental and social consequences (Alley et al., 1999; Hiscock et al, 2002). This SGD definition is more appropriate and get well with the main concept of sustainable development which includes three pillars of environmental, economic and social performances.

The questions are how to provide the decision makers enough information to assist management decisions and how to point out which actions should/should not be taken to improve SGD. In order to find out the appropriate answers for the aforesaid concerns, studies regarding sustainability assessment of groundwater resource are necessary for sustainable groundwater resources management and for sustainable urban development.

1.2. Problem statement and literature review

Sustainability assessment is generally considered as a useful technique to help decision-makers decide the actions they should or should not take in an attempt to make society sustainable (Devuyst et al., 2001). Regarding 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 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 those AHP applications is to categorize and identify the foremost components (criteria, aspects and indicators) that better reflect the significant sustainability performance. In these indicator-based AHP applications on sustainability assessment, the outputs are expressed as sustainability indices because the indices are not only meant to convey a straightforward message to stakeholders and policy-makers but are also able to point out the best practices and the 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 value depends on how the indicators are defined, while its sustainability index should be converted from the indicator values depending on the specific interests of decision-makers. It is, therefore, necessary to introduce a concept to make clear the relationship between an indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature.

Sustainability assessment using indicators are increasingly recognized as a useful tool for policy making and public communication in conveying information on countries' performance in fields such as environment, economy, society, or technical development (Singh et al., 2009). The purpose of sustainability indicators is to help decision makers understand well the economic, environment and social performance and to provide information on how it contributes to sustainable development process (Azapagic, 2004).

Regarding development of a groundwater sustainability indicator, the UNESCO/IAEA/IAH Working Group first tried to define the sustainability indicators of groundwater resources that follow the DPSIR (Driving forces, Pressures, State, Impacts, and Societal Response) 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 mentioned how their indicator values positively or negatively affect three specific sustainable development criteria. Regarding groundwater quantity, for example, one indicator is defined as the ratio between groundwater abstraction and recharge. Physically, this ratio can be used as a sign of groundwater over-exploitation. In terms of benefits for society and economic development, the increase of groundwater abstraction is sufficient to meet the cumulative social demand. This increase, on the other hand, eventually has a series of adverse environmental and social impacts. It is apparently difficult to judge whether the increase of indicator values contributes positively or negatively to the specific sustainability criterion. It is, therefore, necessary to develop appropriate groundwater sustainability indicators from a particular criterion to easily support this judgment.

In Hanoi, Vietnam, the river-streams system is pretty dense, but most of the main rivers and lakes are seriously polluted due to the discharge of industrial, agricultural, aqua-cultural and domestic waste to the water bodies without treatment (Bui et al., 2012a). Groundwater is the most precious and valuable natural resource in Vietnam in general and in the capital Hanoi almost 100% of drinking water is from groundwater resources (Bui, 2011), which means groundwater is vital for socio-economic growth, quality of life and environmental sustainability in Hanoi. However, the rapid groundwater exploitation without an adequate institutionalized management system has caused a series of adverse impacts such as drying up of shallow wells, decline of groundwater level, land subsidence and groundwater pollution in the literature. There have been a number of Hanoi-targeted studies regarding groundwater potential investigation, the aquifer system identification (Bui et al., 2011; Bui et al., 2012a) and serious declined groundwater level trends (Bui et al., 2012b).

Problems associated with groundwater quantity are often accompanied by threats to quality, as the consequences, Hanoi groundwater quality is recently degraded with the prevalence of severe arsenic, nitrogen and coliform contamination (Berg et al., 2001; 2008; Nguyen et al., 2014; Nguyen et al., 2015a; 2015b; 2015c). There have been a number of studies regarding the groundwater pollution situation and its health effects on the community in this target area (Berg et al., 2001; 2008; Bui et al., 2007). However, none of these studies deals with the two important questions mentioned above yet and an appropriate sustainable groundwater management for Hanoi is necessary to secure its availability as well as its economic, social and ecological values. In the case of sustainable urban development, sustainability assessment can provide a certain level of awareness on the benefits of environmental, social and economic sound. Specifically, there have been no such AHP sustainability assessment studies carried out for groundwater resources so far. The common practice of sustainability assessment in Vietnam is generally qualitative and lacks clear methodology in evaluating multi-criteria systems. Therefore, a study that deals with sustainability assessment in Hanoi is necessary to find the solutions that may help to cope with these inadequacies.

1.3 Objectives, scope, and methods

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. Based on these above-mentioned reasons, this dissertation focuses on the following main objectives: (i) to develop an indicator-based AHP for sustainability assessment of groundwater resources (AHP-SAG) to cope with the limited data availability and reliability, and insufficient financial supports in the developing countries like Vietnam; (ii) to develop a clearly defined sustainability assessment framework including the utmost sustainability goal, associated with its sustainability criteria, aspects and indicators for groundwater resources of Hanoi by using the proposed AHP-SAG; (iii) to apply the proposed AHP-SAG framework for a reasonable sustainability assessment of groundwater resources in Hanoi.

For the first objective, we modified and developed an AHP-sustainability assessment for groundwater resources approach (AHP-SAG) based on the usual steps in the conventional AHP application for sustainability assessment. Usually, there have been four basic steps in sustainability assessment using the commonly used AHP approach, in which the second one is to weight the relative contribution of each sustainability component to the sustainability goal by consulting experts. The conventional way of determining these relative contributions is very tedious and especially carrying out such complicated surveys regarding groundwater sustainability seems to be difficult without enough financial support in Vietnam. So that we modified the conventional AHP to make it simple by flexibly weighting the contribution of each component weights by a function of the number of components. We then introduced a concept of sustainability index function (SIF) to make clear the relationship between the component value and its sustainability index. We considered not only the conventional linear relationship as it is usually examined in the literature but also a non-linear one to find out a reasonable sustainability assessment. The AHP-SAG development is necessary to heal the research gaps which are existed in the sustainability assessment literature mentioned above.

For the second and third objectives, we developed the components of the sustainability hierarchy for groundwater resources of Hanoi based on the two following considerations. The first consideration is the AHP concept in which the components of the hierarchy are defined as the conceptual levels from the highest to the smallest. The highest level is the ultimate goal (sustainability goal, in this case). The next below levels are criteria which are main aspects to archive the ultimate goal. The smallest levels are called indicators which are the detailed components of how to archive the criteria, independently to other criteria. The indicators are conceptually and practically measurable. Based on this concept, the main criteria were selected as environmental, economic and social. In each criterion, the aspects of quantity, quality and management were mainly considered; and the environmental, economic and social sustainability indicators were appropriately selected according to the current situation of groundwater usage and development in Hanoi. In this study, the current main problems of groundwater development and use are the second consideration for sustainability indicator development. Finally, based on the results of sustainability assessment, a reasonable sustainability assessment was point out and the recommendations of improving sustainable groundwater resources for Hanoi was provided.

1.4 Outline of the dissertation

This dissertation is composed of five chapters.

Chapter 1 was comprised of the background, motivation, and objectives of this study. A comprehensive review of literature and a description of the scopes and methods were presented.

Chapter 2 focused on current sustainability issues of groundwater resources in Hanoi, Vietnam. A brief description of the basic topographical conditions, current situation of domestic water uses, and groundwater conditions of Hanoi was provided.

The environmental and socioeconomic sustainability issues of groundwater in Hanoi were comprehensively reviewed and presented.

Chapter 3 proposed a sustainability assessment framework for groundwater resources, which was mainly developed from the AHP. In the proposed AHP-SAG, weighting process, the most tedious step in the conventional AHP applications was modified to make it simple. Generally, the weights refer to the relative contributions of the components to the final goal of sustainability. The weighting process based on the conventional AHP is very tedious due to finding the appropriate experts, waiting for their big efforts to make the large series of pairwise comparison judgments, and even ask the experts to repeatedly make the judgments until acceptably consistent judgments are obtained. In developing countries like Vietnam, however, carrying out such complicated surveys regarding groundwater sustainability seems to be difficult without enough financial support. Therefore, in this chapter, we modified the conventional AHP to make it simple by flexibly weighting the contribution of sustainability framework components to the final goal by a function of the number of aspects and indicators. In addition, based on the literature of AHP-based sustainability assessment 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 value depends on how the indicators are defined, while its sustainability index should be converted from the indicator values depending on the specific interests of decision-makers. Therefore, a necessary concept of sustainability index function (SIF) was introduced to make a clear relationship between an indicator value and its sustainability index, which has remained unclear in the sustainability assessment literature. In sustainability assessment studies, a reasonable assessment is the one whose results could reflect appropriately the actual situation in reality. So in this Chapter, not only the linear SIF, which was usually carried out in the conventional AHP application for sustainability assessment, but also the non-linear SIF cases were also investigated to find out a reasonable sustainability assessment for groundwater resources. The proposed AHP-SAG approach is described in detail in this chapter.

Chapter 4 dealt with the applications of the proposed AHP-SAG technique in sustainability assessment of groundwater resources in Hanoi, in which all the three main pillars (environmental, social and economic) of sustainability concept were considered as the three important sustainability criteria in the framework. Based on the available and reliable data of the current groundwater situation in the target area, the sustainability aspects were proposed as quantity, quality, and management in each criterion. Furthermore, the sustainability indicators in each aspect were defined clearly, which could present the overall situation of groundwater resources development in Hanoi.

For sustainability assessment, the environmental, social and economic criteria were composed of their twelve, thirteen and nine (34 in total) core sustainability indicators, respectively. By gathering the necessary data, environmental, social and economic sustainability assessment of Hanoi was investigated by using the proposed AHP-SAG. It was found that the sustainability indices assessed by the combined linear and non-linear SIF case were more reasonable than the conventional linear SIF alone because the sustainability indices properly reflected the current groundwater problems in Hanoi. The environmental, social and economic criteria were appropriately assessed at acceptable, acceptable, and good sustainability levels, respectively. Lastly, the all-purpose sustainability index was assessed at acceptable level. However, there was a big variation among the 34 sustainability index values of indicators. Some indicators were assessed closely to the poorest but the others were even reaching the most excellent sustainability levels. The variability of the environmental sustainability indices indicated that the current groundwater abstraction networks are heavily concentrated to some specific areas in Hanoi, which is not successful to utilize the rich recharge from nature. From the social viewpoint, the communities are satisfied with the quantity but dissatisfied with the current poor quality and the relative high water prices. Some economic indices revealed that there was a considerable economic loss due to the ineffective water supply in the target area. The proposed AHP-SAG method thus provided a clear panoramic view of the environmental, social and economic impacts on sustainability of groundwater resources in Hanoi; so that the sustainability assessment could be a more helpful baseline for any further assessment of Hanoi's groundwater.

Chapter 5 presented the overall conclusions and recommendations for sustainable groundwater resources management in Hanoi, including the future research works.

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CHAPTER 2

CURRENT SUSTAINABILITY ISSUES OF GROUNDWATER RESOURCES IN HANOI, VIETNAM

2.1 Basic conditions of Hanoi

In Vietnam, groundwater has become the most important water supply source, especially in the fast-urbanizing capital, 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.2-1**. Hanoi is located in the northeastern part of Vietnam covering an area of 3324.5 km^2. Its population of more than 7.2 million (2015) accounts for almost 10% of Vietnam's total population, with a population density of more than 2,000 people/km^2 (General Statistic Office of Vietnam, 2015), the highest in Vietnam. Hanoi area has been extended since 2008 and it is devided into the urban and sub-urban districts. The urban districts are mainly located in the metropolitan areas and several newly urbanized districts wheres the sub-urban ones are mainly located in the former Hatay and Vinhphuc provinces.

Hanoi belongs to the tropical monsoonal area with two distinctive annual seasons, the rainy and dry seasons. The average discharge of the Red River at the Hanoi station is 1160 m^3/s during the dry season and 3970 m^3/s during the rainy season (IMHE-MONRE, 2011). The annual average rainfall is about 1,600 mm and 75% of which occurs during the rainy season; the average humidity is about 80%; and the average temperature is about 24.3ºC. Evaporation is quite high with an annual average of 933 mm. Hanoi as a part of the Red River Delta (RRD) 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 (Bui et al., 2011).

According to the previous study (Bui et al., 2012a) regarding groundwater quantity aspect, Hanoi groundwater resources mainly exist 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. In HUA layer, silty clay and various kinds of sands mixed with gravels are the main components. The HUA thickness is variously distributed, more than 35 m with an average of 15 m, approximately. The transmissivity and the specific yield of this layer ranges from 20 to 1,788 m^2/day and from 0.01 to 0.17, respectively. The HUA, thus, is distributed at a rate of about 55% in the south of the city area, and has a relatively high potential of groundwater resources, sufficient for the small to medium scale domestic water supply. The shallow PCA depth is also widely distributed, less than 10 m in the North of the Socson district, around 20 m in Dong Anh, and up to 40 m in the south of the Red River. The PCA layers have a complex components of sand mixed with cobbles and pebbles. The PCA thickness is variously changed, with the highest value of up to 50m and the average of 35 m approximately and trend increasing from the North to the South. With a large range of transmissivity from 700 to 2,900 m^2/day, and the specific storativity from 0.00004 to 0.066, PCA is the highest potential of groundwater resources and widely distributed at a rate of about 80% in the south of the city, serving the most important aquifer for the area water supply (Bui et al. 2012a).

The HUA and PCA are mainly recharged by the Red River within the 5 km, other than 5 km, the surrounding mountain range and the vertical percolation of water coming from HUA recharge for PCA, in which the former is the main recharger. According to another the previous study, Bui et al. (2011), HUA groundwater levels are usually situated within 4 meters under the ground surface and we explored that the groundwater level of the PCA showed a rapid decline speed of 0.2 m/year approximately.

Fig. 2-1 Study area and main rivers and lakes in Hanoi.

2.2 Environmental sustainability issues of groundwater in Hanoi

As one of cities having the highest density of population in Vietnam, Hanoi urbanization process is rapid. This increasing trend leads to an ever-big social demand of natural resources, especially water resources with ever-increasing domestic and industrial waste generated.

According to the previous study (Bui et al., 2012a) regarding groundwater quantity aspect, Hanoi groundwater resources mainly exist in the topmost Holocene unconfined aquifer (HUA) and the Pleistocene confined aquifer (PCA). The HUA with its distribution area of 1,499 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 3,703 km^2 accounts for the highest groundwater potential, serving the most important aquifer for the area 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 1,028.52 mm/year at Tay Ho district, and an average recharge estimation of about 276 mm/year (equal to 2,513,868 m^3/day). The abovementioned study revealed the serious decline in groundwater levels in this area. Specifically, the estimated area with the occurrences of declined groundwater levels is 634.79 km^2 approximately, 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 is reaching 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, which are in danger of wiping away groundwater resources, according to the latest report of the current groundwater problems in Hanoi from NAWAPI (2017). Consequently, land subsidence occurs over a 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. In terms of quantity, the environmental impact areas in HUA is thus more serious than the ones in PCA. The rapid groundwater exploitation without an appropriate management system has been considered as a significant cause of these adverse impacts (Bui et al., 2012b). As an economic and political central of Vietnam, Hanoi has been experiencing the dramatic increases in population, agricultural and industrial activities, and urbanization process, which also put much more stress on the groundwater quality (Li et al., 2017).

Hanoi groundwater resource has reported as a seriously degraded sources in both quantity (Bui et al., 2012b; NAWAPI, 2017) and quality (Berg et al., 2001; Nguyen et al., 2015b; NAWAPI, 2017) as the certain consequences of inappropriate usage and management manners. As for the results of a series of our groundwater quality assessment studies in Hanoi and its adjacent provinces, the resource has been 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; Nguyen et al., 2014; Nguyen et al., 2015a; Nguyen et. al., 2015b; Nguyen et. al., 2015c; NAWAPI, 2017). Saltwater intrusion is also the other concern in this area. The groundwater areas in PCA is 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 saltwater intrusion) than the ones in HUA. There are a series of publications and government reports concerning arsenic contamination groundwater and its adverse human health impacts in Hanoi and its surroundings; Hanoi government tries hard not only to control the ever-increasing groundwater abstraction, improve the current groundwater quality, but also recommend the communities to use the advanced water purifiers as the best treatment system and/or the sand filter metal removal technique before use the water for domestic purposes.

2.3 Socioeconomic sustainability issues of groundwater in Hanoi

According to the previous study (Bui et al., 2012a) regarding groundwater quantity, the groundwater resources of Hanoi exist mainly in the topmost HUA and 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.

In terms of economic development, groundwater in Hanoi is the most important water supply sources accounting 93% of domestic water use contribution for the communities (HAWACO, 2014). The resource also significantly contributes to Hanoi industrial and service sectors with a high proportion of 77% (MONRE, 2016). Currently, up to 632,172 m^3/day of groundwater is exploited for water supply purpose (MONRE, 2016). Hanoi groundwater not only contribute to domestic water use but also contribute to industrial and service. According to MONRE (2016), approximately 693,572.7 m^3/day of groundwater is abstracted for industrial and service purposes; expecting that the industrial water demand will be about 82,000 m^3/day in 2020 (No.499/QD-TTg, March 21, 2013). As presented in the previous section 2.2 of this chapter, these serious quantity and quality degradations require a certain budget for groundwater abstraction, appropriate treatment and long-term remediation, thus threatening the community's goal of sustainable groundwater development. That is one of the reasons why Hanoi government recently tries hard to reduce this pressure on groundwater abstraction by establishing a number of surface water treatment plants which use the surface water resources from rivers in Hanoi and nearby.

2.4 Conclusions

Groundwater resources play a key role in general socioeconomic growth and environmental development of Hanoi and the RRD. Groundwater resources has been the primary sources for daily water supplies, industrial and service sectors of Hanoi communities. In order to adapt to the rapid urbanization and industrialization of the capital in the developing countries like Vietnam, the amount of groundwater abstraction has been increasing dramatically. In the absence of adequate groundwater withdrawal distributions and effective management system, a series of adverse impacts on environmental such as the unmitigated decline of groundwater levels, land subsidence, saltwater intrusion, and degradation of groundwater quality has been occurred. Consequently, the environmentally adverse impacts affect to socioeconomic conditions for Hanoi communities. Land subsidence occurrences, for instance, cost more investment on other economic sectors, construction is an example; groundwater declines make the pumping cost increased; especially, serious groundwater pollution not only requires more budget for appropriate treatments before using for domestic purposes but more importantly, it will harmfully affect to the community health in both short- and long-term exposures. Both the groundwater quantity and quality degradations in Hanoi not only threaten sustainable environment of the local aquifer systems, require more cost of resource development and preservation, but also life-threaten to the Hanoi communities for ensuring sustainable society. Therefore, it is absolutely important to investigate such intensive studies, in which, the sustainability problems (all environment and socioeconomic perspectives) of the groundwater in Hanoi are analytically reviewed and assessed to provide fundamental information for evidence-based decisions towards a sustainable groundwater management and development.

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CHAPTER 3

PROPOSAL OF SUSTAINABILITY ASSESSMENT FRAMEWORK FOR GROUNDWATER RESOURCES (AHP-SAG)

3.1 Analytical Hierarchy Process (AHP) and its application on sustainability assessment

3.1.1 AHP

Multi- Criteria Decision Making (MCDM), is “the study of methods and procedures concerning about multiple conflicting criteria, which can be formally incorporated into the management planning process", as defined by the International Society. Multi-criteria Decision Analysis has been widely used to evaluate sustainability (Liu, 2007; Shmelev and Rodrigues, 2009), and it has been considered as a proper approach for sustainability assessment (Boggia and Cortina, 2010). MCDM is one of the well-known topics of decision making, and a modeling and methodological tool for dealing with complex problems (Kahraman, 2008). In its most basic form, MCDM assumes that a decision maker is to choose among a set of alternatives whose attributes are known with certainty. MCDM problem concerns the revelation of preference levels of alternatives through judgments, which are made over the number of criteria of MCDM problems. At the decision-maker level, a useful method for solving MCDM problem must consider opinions made under uncertainty and based on distinct criteria with different importance.

Analytic Hierarchy Process (AHP) is one of the most popular and powerful methods for MCDM (Saaty, 2001). Established by Dr. Saaty in 1977, AHP is a methodology consisting of structuring, measurement and synthesis, which can help decision makers to cope with complex situations. AHP is a multi-criteria decision making approach that simplifies complex, ill-structured problems by arranging the decision factors in a hierarchical structure. The AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution (Vaidya and Kumar, 2006). The AHP has been used as a widespread decision-making analysis tool for modeling unstructured problems in areas such as political, economic, social, and management sciences (Yu, 2002). It helps the decision makers to find the decision that best suits his/her needs and his/her understanding of the problem (Saaty, 1977). AHP provides a comprehensive and rational framework for structuring a decision problem, representing and quantifying its elements, relating those elements to overall goals, and evaluating alternative solutions.

The basic idea of AHP is to decompose a decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. Once the hierarchy is built, the decision makers evaluate the various elements of the hierarchy by comparing them to one another two at a time (Saaty, 2008). In making the comparisons, the decision makers can use both objective information about the elements as well as subjective opinions about the elements' relative meaning and importance. The AHP converts these evaluations to numerical values that are processed and compared over the entire range of the problem. The main advantage of AHP with respect to other decision making techniques is that the numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. At its final step, numerical priorities are calculated for each of the indicators (Bui et al., 2011).

For more details, AHP consists of three main operations, including hierarchy construction, priority analysis, and consistency verification. This conventional approach can be described as following steps. First of all, the decision makers need to break down complex multiple criteria decision problems into its component parts of which every possible attributes are arranged into multiple hierarchical levels. After that, the decision makers have to do pairwise comparisons at the same level of hierarchy, using Saaty's scale of absolute numbers which is used to assign numerical values to both quantitative and qualitative judgments (**Table 3-1**).

Table 3-1 Saaty's scale for pairwise comparisons

Saaty's scale (from 1 to 9)	The relative importance of the pair of elements at the same level
1	Equally important
3	Moderately important with one over another
5	Strongly important with one over another
7	Very strongly important with one over another
9	Extremely important with one over another
2, 4, 6, 8	Intermediate values

The results of these comparisons are recorded in a ($n \times n$) positive reciprocal matrix A, where the diagonal $a_{gg} = 1$ and the reciprocal property: $a_{gh} = 1/a_{hg}$ where g, h = 1. . . n.

$$A = \begin{bmatrix} 1 & . & . & . \\ . & 1 & a_{gh} & . \\ . & 1/a_{gh} & \cdots & . \\ . & . & . & . \\ . & . & . & . \end{bmatrix}$$

Since the comparisons are carried out through personal or subjective judgments, some degree of inconsistency may be occurred. To guarantee the judgments are consistent, the final operation called consistency verification, which is regarded as one of the most advantages of the AHP, is incorporated in order to measure the degree of consistency among the pairwise comparisons by computing the consistency ratio.

3.1.2 The four major steps in the conventional AHP applications for sustainability assessment

Since establishment, AHP has been successfully applied in a various application fields of multifaceted and unstructured political, economic, social, and management sciences problems. Particularly, AHP has been usually used for various sustainability assessment projects including 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 these complex sustainability problems (Yu, 2002). The main advantage of those AHP applications is to categorize and identify the foremost components (aspects and indicators) that better reflect the significant sustainability performance. There are four basic steps in sustainability assessment using the commonly used AHP approach.

The first step in the standard AHP application is to create a hierarchy of components by breaking down the ultimate goal, MCDM problem of sustainability, into its aspects and indicators in each aspect.

The second step in the standard AHP application is to weight 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 the acceptably consistent judgments are obtained.

The third step is to collect the actual data and transformation. The input indicator values vary, a transformation method thus is needed to make those values dimensionless and in the range of 0 to 1. The transformed values are then automatically considered as their indicator sustainability indices.

The fourth step is to assess sustainability performance.

3.2 Proposal of AHP based sustainability assessment for groundwater (AHP-SAG)

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

3.2.1 Step 1: Build up a sustainability hierarchy

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

3.2.2 Step 2: Modified weighting process

Generally, the weights refer to the relative contributions of the components to the final goal of sustainability, as mentioned in the conventional AHP applications. The conventional way of determining these relative contributions is very tedious due to the need to (i) find the appropriate experts, (ii) wait for their big efforts to make the large series of pairwise comparison judgments, especially in 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; Bui et al., 2018a; b) 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 criteria, aspects and indicators. For the simplest weighting case, particularly in this study, the criterion, aspect and indicator weights are equally evaluated as the first trial by using the following equations, Eqs. (1), (2) & (3).

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

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

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

with the constraints:

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

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

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 criteria; 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 is not 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 automatically derived by the number of GSC, GSAs and GSIs. This equally weighting process thus provides a quick view of the current groundwater status and can be easily applied to other areas.

3.2.3 Step 3: Data collection and sustainability index function (SIF)

Similarly with the conventional AHP sustainability assessment applications, the third step of the proposed AHP-SAG approach is also to collect the actual data for evaluating the indicator values. In this study, however, this step by clearly defining an SIF as an indicator to clarify the relationship between the indicator value and its sustainability index as follows.

Defining SIF for indicator

Normally, the sustainability indices have varied from 0 to 1 in the literature (Bui et al., 2017; Pandey et al., 2011; Singh et al., 2007; Si et al., 2010). 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 **Chapter 4**, the SGI_{111} indicator is related to the relationship between groundwater abstraction and recharge. Reasonably, GSI_{111} 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 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.

SIF is defined as a function of indicator value x: $\Omega_I = f(x)$

Fig.3-1 shows the visualization of SIF in the following two cases, which are named Linear SIF and Non-linear SIF. Linear SIF case: SIF is defined as a linear relationship between the indicator value and its sustainability index, which is usually used in the conventional AHP applications. In this case, the SIF is expressed as follows.

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

Non-linear SIF case: 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 monotonic increase function with x; (ii) it should be zero at $x = 0$, and (iii) should be 1 at $x = 1$. As far as satisfying these three conditions, any type of function is acceptable, the general exponential function thus 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_α = 0; α = 0) and (x_α = 1; α = 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 differ from problem to problem.

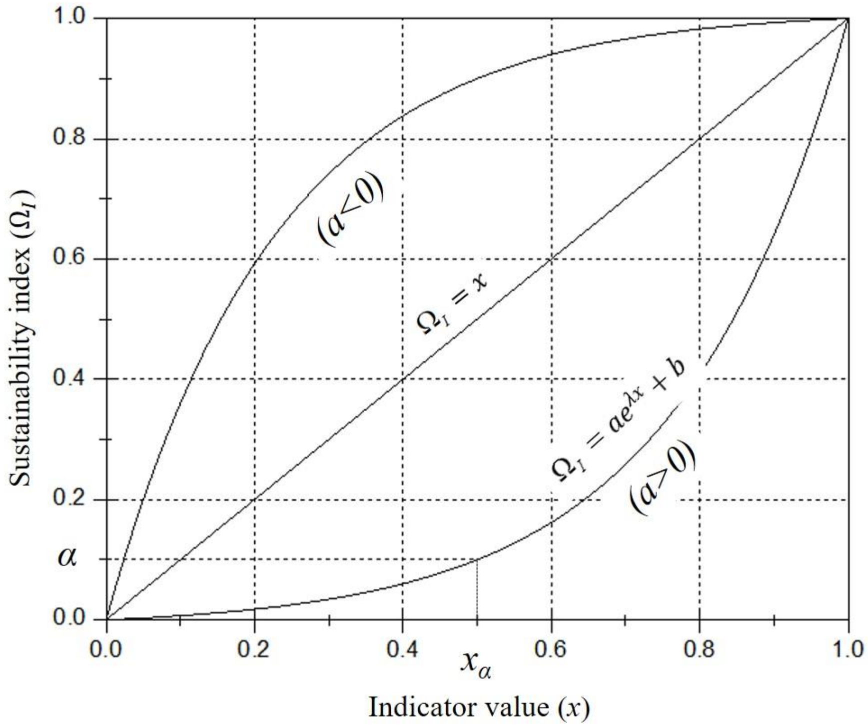

Fig. 3-1 Visualization of SIF based on the linear and non-linear relationships.

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

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

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

$$b = -\frac{1}{e^{\lambda}-1} \tag{10}$$

$$\alpha e^{\lambda} - \alpha - e^{\lambda x_\alpha} + 1 = 0 \tag{11}$$

3.2.4 Step 4: Sustainability assessment

The sustainability index of the k^{th} indicator in the j^{th} aspect of the i^{th} criterion is evaluated based on the specific considerations for the criteria, aspects, indicators, and the sustainability goal. Once all the components of the sustainability hierarchy and SIF for indicators are determined, it can be simply calculated according to the actual data. The sustainability index $\Omega_A(i,j)$ for the j^{th} aspect of the i^{th} criterion and the final sustainability index Ω are evaluated by using the following equations, (12), (13) and (14), respectively:

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

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

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

So, naturally, sustainability indices Ω, Ω_C, Ω_A, and Ω_I are in the range of 0 to 1 and usually categorized into several classes known as sustainability scales. In this study, we adopt the sustainability scale, which is shown in **Table 3-2** (Bui et al., 2016; 2018a; b).

Table 3-2 Sustainability scale

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

3.3 Conclusions

There is a mounting concern about how to support decision-makers in driving a sustainable water resources management and science needs to support decision-making process to promote evidence-based decisions. To this end, sustainability assessment is considered a useful technique provide sufficient information to assist management. This study aims to propose a general sustainability assessment framework for groundwater resources which corporates with the concept of a usually effective approach for sustainability assessment studies, the AHP.

To do that, we modified the conventional AHP approach into the AHP-SAG approach. In the proposed AHP-SAG approach, the most tedious weighting process by consulting expert's opinions of the standard AHP was simplified to cope with the limited data availability of the developing countries like Vietnam. We improved the sustainability assessment by introducing a concept of SIF to clarify the relationship between indicator value and its sustainability index, which has been remained unclear in the sustainability assessment literature. The introduced SIF concept was needed because the usual consideration of an indicator value as the same as its sustainability index was 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. So by introducing the concept of SIF, this usual consideration was formed as a linear SIF case. We introduced a non-linear SIF to find out a reasonable sustainability conversion. The proposed sustainability framework has been applied to Hanoi case study by gathering available data to test the result's reflectivity to the actual problems by linear and non-linear relationship SIF cases. A reasonable sustainability assessment, which could reflect the actual situation of groundwater problems in Hanoi, is essential to make the assessment results more helpful to the decision-makers.

However, as mentioned in the methodology, the condition 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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CHAPTER 4

SUSTAINABILITY ASSESSMENT OF HANOI GROUNDWATER BY THE PROPOSED AHP-SAG

In the AHP approach, generally, the most important step is to identify the main components in the sustainability hierarchy (Step 1). In this study, we carefully selected the indicators and aspects for groundwater sustainability assessment based on the consideration of the current situation actual problems occurred and expected goal (Chen et al., 2015). The more complex indicators system can be developed if the more actual data are available.

4.1 Environmental Sustainability Assessment

Sustainability concept has been reviewed by its three main pillars of environmental, economic and social performances; in which environmental sustainability usually gains a massive attention from scientists, governmental decision makers, and practitioners worldwide. The reason for this attention trend is probably that a sustainable environment could be considered as a necessary prerequisite to a sustainable socio-economic system (Morelli, 2011). There has been a big effort in deriving an appropriate definition of environmental sustainability (Fulton et al., 2017; Liu, 2007; Moldan, et al., 2012; Morelli, 2011; Sutton, 2004; World Bank, 1991; 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 a sufficient quantity and quality of groundwater 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 more than two billion people depend on groundwater for their daily water supply, and over half of the global population depends on it for drinking (United Nations, 2015). Along with the ever-increasing human needs, the amount of groundwater abstraction has been rapidly and continuously increasing worldwide. There are a series of severe problems related to groundwater over-exploitation such as occurrences of groundwater decline, land subsidence, groundwater pollution and health hazards (Gupta and Onta, 1997). So achieving sustainable groundwater management and specifically, achieving environmental sustainability for the groundwater development is one of the challenges and one of the vital goals for the future of many countries.

It is apparent that science needs to support 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 the decision-makers sufficient information to assist management decisions to improve the environmental sustainability. Environmental sustainability assessment is a useful technique to find out the appropriate answers to the aforementioned concerns. Regarding sustainability assessment methodologies, Analytical Hierarchy Process (AHP) is a useful approach dealing with multifaceted and unstructured sustainability problems (Boggia and Cortina, 2010; Yu, 2002). AHP has been successfully applied to various application fields and specifically for water resources, it mostly has been developed and utilized for a specific sustainability pillar such as environmentally sustainable evaluation of the water pollution which is impacted from mining sites (Si et al., 2010), regional water resources (Sun et al., 2016), economic (Bui et al., 2017b) and/or social sustainability assessment of groundwater resources (Bui et al., 2018). However, AHP has not been employed for an integrated sustainability assessment for groundwater resources in the literature, in which all the three sustainability pillars 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 goal, the lower one of the goal's features (criteria), then the criterion's main characteristics (aspects), to the smallest level component (indicators) is one of the most difficult tasks. The criteria could be conceptually referred as the three main sustainability pillars (environmental, social and economic) (Bui et al., 2017a). The aspects and indicators should be developed appropriately based on the current situation 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, and 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 to one of the three specific sustainability pillars (environmental, social and economic). Regarding groundwater quantity, for example, one indicator is defined as the ratio between groundwater abstraction and recharge. Conceptually, the recharged groundwater could be constant within a boundary condition of a specific area such as climate, rainfalls, soil features, etc. So that the increase of groundwater abstraction is good to meet the cumulative social demands. This increase, however, eventually lead a series of adverse environmental impacts like groundwater level declined, land subsidence and even pollution. It is apparently difficult to judge whether the increase of indicator values positively or negatively contributes to one of the specific sustainability pillars. It is, therefore, necessary to develop a set of the appropriate groundwater sustainability indicators from a particular pillar (environmental criterion in this case) to support the judgment easily. The groundwater environmental sustainability indicators (GSIs) should be selected according to the current environmental problems of the target groundwater resources and should be appropriately defined.

4.1.1 Environmental Groundwater Sustainability Aspects

In the AHP approach, generally, the most important step is to identify the main components in the sustainability hierarchy (step 1). To identify the relevant environmental sustainability issues, it is essential to explore the current problems of groundwater usage and management in Hanoi from the environmental point of view. In **Chapter 2** of this dissertation, the current environmental problems of groundwater resources in Hanoi have already been presented. These quantity and quality degradations apparently 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. Therefore, in this study, the considerations of groundwater quantity, quality and management concepts are deemed as the three main environmental GSAs reviewing the focal features of the environmental sustainability target. It is quite difficult to judge which GSA is more important to contribute to the environmental sustainability goal than the other one, so that in this study the three GSAs are given equal importance. We then carefully selected environmental GSIs for each environmental GSA based on the consideration of the current situation actual problems occurred and expected goal in the target area. The more complex indicators system could be developed if the more actual reliable data are available.

4.1.2 Environmental sustainability indicators

Data are essential to develop integrated approaches for sustainable groundwater management (Rossetto et al., 2007). In a developing country like Vietnam, however, the data related to the sustainability of groundwater management is sparse, seldom systematically organized, and accessible to a very limited number of official users (Bui et al., 2018). In this study, we actually exerted much effort to gather the necessary data and more importantly to keep the data consistent. The primary data sets come from the Vietnamese government database, and local and national environmental agencies. The input data we used are authorized and reliable from the national project of "Groundwater Protection in the Big Cities, Hanoi" which has been investigated by National Center for Water Resources Planning and Investigation (NAWAPI) under the supervision of Ministry of Natural Resources and Environment since 2017, The Ministry of Science and Technology in 2017, Hanoi Statistics Office in 2017, Hanoi Sewerage and Drainage Limited Company in 2017 and a several Hanoi groundwater targeted studies in 2014 and 2015. Therefore, the input data used in these proposed indicators are reliable in the 4-year duration of (2014-2017) in Hanoi, Vietnam. Based on the criteria of data availability and reliability, the low reliability data (too old or from the unpublished works) were screen out, only the up-to-date, authorized and reliable data are utilized for indicator development, as follows.

In terms of the quantity aspect (GSA_{11}), which is a measure of how much abstracted groundwater compared to its recharge, exploitable amounts and the consequences of groundwater over-exploitation. As guided by the UNESCO/IAEA/IAH Working Group (Vrba and Lipponen, 2007), the indicators regarding to these ratios between abstraction to recharge and 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 are followed the rule of "the bigger GSI value, the better its contribution to the environmental sustainability goal"; the first two indicators of the quantity aspect are defined as follows.

$$GSI_{111} = \begin{cases} 1 - \frac{\text{Total abstraction}}{\text{Total recharge}} & \text{if the abstraction} \leq \text{the recharge} \\ 0 & \text{if the abstraction} > \text{the recharge} \end{cases} \quad (15)$$

$$GSI_{112} = \begin{cases} 1 - \frac{\text{Total abstraction}}{\text{Exploitable groundwater}} & \text{if the abstraction} \leq \text{the exploitable} \\ 0 & \text{if the abstraction} > \text{the exploitable} \end{cases} \quad (16)$$

By these definitions, the environmentally sustainability contributions of GSI_{111} and GSI_{112} are maximized at ones if there is no groundwater abstraction, and minimized at zeros at occurrence of groundwater over-exploitation. For the next three indicators GSI_{113}, GSI_{114} and GSI_{115}, according to the current situation of groundwater problems presented in the previous **Chapter 2**, these indicators are focused on groundwater declined area, critical zone (area with the groundwater levels less than 5 m (suggested by Hanoi's No.161/QĐ-UBND from the threshold level) and land subsidence area proportions, respectively. By these index-based definitions, these indicator values are in the range of 0 to 1 and follows the positive correlation with their sustainability indices. So the five environmental sustainability indicators of the first aspect (GSA_{11})

and their index-based definitions are shown in **Table 4-1**.

For the quality aspect GSA_{12}, it is a measure of how much contaminated groundwater area proportions 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 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. In the literature of groundwater quality in Hanoi, it is recently concerned four major contamination agents of arsenic, nitrogen, iron and manganese, and saltwater intrusion. So that for this quality aspect, four indicators needed to be considered to measure how much in percentage of these contaminated/intruded areas to the total study area. For example, the first indicator GSI_{121} of this quality aspect corresponds to arsenic contamination is defined as one minus the proportion of area with arsenic-contaminated groundwater to study area to make its value within the range of 0 to 1 and follow the positive correlation with its sustainability index (**Table 4-1**).

For the management aspect GSA_{13}, 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. The three indicators of the management aspect are about how the government reduces the pressure on groundwater resources at which the social need is still qualified; how much in percentage that the environmental laws are obeyed in actual implementation; and how strength of the current human resources is in the water-related fields specifically and in the natural resources and environmental fields generally. Finally, three main GSAs (quantity, quality, and management) and their respectively five, four, and three corresponding GSIs shown in **Table 4-1** are proposed to build the environmental sustainability hierarchy for Hanoi groundwater based mainly on the current problem consideration from the environmental point of view.

Table 4-1 Environmental sustainability aspects and indicators for Hanoi groundwater resources

GSA	GSI	Consideration	Index-based definition
Quantity (GSA_{11})	GSI_{111}	Abstraction-recharge relation	One minus the ratio of groundwater abstraction to groundwater recharge if this ratio is less than 1, otherwise 0 (Eq. (15)).
	GSI_{112}	Abstraction-exploitable relation	One minus the ratio of groundwater abstraction to exploitable groundwater resources if this ratio is less than 1, otherwise 0 (Eq. (16)).
	GSI_{113}	Declined level	One minus the proportion of area with decline of groundwater level caused by groundwater over-exploitation
	GSI_{114}	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_{115}	Land subsidence	One minus the proportion of area with land subsidence occurrence caused by groundwater over-exploitation
Quality (GSA_{12})	GSI_{121}	Arsenic contamination	One minus the proportion of area with arsenic-contaminated groundwater
	GSI_{122}	Nitrogen contamination	One minus the proportion of area with ammonium, nitrate dioxide and nitrate-contaminated groundwater
	GSI_{123}	Fe and Mn contamination	One minus the proportion of area with iron and/or manganese contaminated groundwater
	GSI_{124}	Saltwater Intrusion	One minus the proportion of area with groundwater saltwater intrusion
Management (GSA_{13})	GSI_{131}	Reducing pressure	Proportion of budget allocation for reducing pressure on groundwater resources
	GSI_{132}	Environmental law enforcement	Proportion of environmental law obeyed
	GSI_{133}	Water-related human capacity	Proportion of the current number of people who are working for water related field

4.1.3 Results and Discussion

According to the index-based definitions of the indicators described in the previous section, we then calculated the indicator values, which are shown in **Table 4-2**. The following sub-sections explain procedures for obtaining the environmental sustainability indices (ESIs) for Hanoi groundwater from both conventional linear relationship and non-linear SIF. Hereafter, the conventional relationship is expressed as the linear SIF.

4.1.3.1 Linear SIF case

In the case of the linear SIF in Eq. (6), 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 4-2**.

In the quantity aspect (GSA_{11}), GSI_{111} and GSI_{112} are assessed respectively at acceptable and excellent sustainability levels of 0.54 and 0.87 according to the sustainability scale shown in **Table 3-2**. These assessments indicate that the proportions 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), the groundwater could be considered as “low development” if the abstraction-exploitable ratio is less than 90%. For the abstraction-recharge ratio, even the abstraction is reaching to be equal to the recharge, there will be also no environmental impacts of groundwater level declines. From the environment point of view, the less groundwater is abstracted, the better ESI should be. In Hanoi case, therefore, to be corresponding to the “low” status of the groundwater development, 0.54 value for GSI_{111} should be assessed at the excellent sustainability levels and the abstraction amount could be increased even much more than the current one to meet the social satisfaction. In short, the sustainability assessments of GSI_{112} is reasonable while the one for GSI_{111} is not quite suitable to reflect the “low development” of Hanoi groundwater. The indicator GSI_{113} is assessed at the excellent sustainability level of 0.81, suggesting that the areas with declined groundwater levels occupied about 20% of Hanoi. The indicator GSI_{114} and GSI_{115} are also assessed respectively at good and acceptable sustainability levels of 0.77 and 0.42, 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 the previous **Chapter 2**, 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_{114} is not quite suitable in Hanoi case and more appropriate assessment is needed to reflect the actual situation reasonably. Consequently, the ESI of the quantity aspect GSA_{11} is assessed at a good level $\Omega_A(1,1)$ of 0.68.

Similarly, in the quality aspect (GSA_{12}), all the indicators are assessed at more than acceptable sustainability level. The first three indicators reading arsenic, nitrogen and other metal (Fe and Mn) contaminations are respectively assessed at excellent, excellent and good sustainability levels. The last indicator GSI_{124} related to saltwater intrusion situation is also assessed at an excellent level of 0.90. As a result, the sustainability index of the quality aspect is assessed at an excellent level of 0.84. So based on the linear SIF of Eq. (6), it means that, 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 the quality point of view, as described in the study area, there are a series of publications and government reports concerning heavy metal (arsenic), nitrogen (especially NH_4^+) , and other metals (Fe and Mn) contamination of groundwater and its adverse human health impacts in Hanoi and its surrounding. 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., 2018a). Therefore, the ESIs based on the linear SIF of the indicators regarding the risk of contamination areas 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_{13}), GSI_{131} and GSI_{133} are assessed at 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 a number of surface water treatment plants (reaching up to 516.6 million USD approximately in 2014-2017 according to Ministry of Science and Technology (2015)) that take water sources from rivers in and near the capital, these projects apparently could reduce pretty much the current high pressure on groundwater resources once getting operated. On the other hand, they also expand their water/natural resources and environment authorities (universities, institutes, national centers, etc.) to enhance the education of the relevant human resources. However, as a usual situation regarding law enforcement of the developing countries like Vietnam, the environmental law is quite inappropriately strict in implementation. In Hanoi case, while the government regulates that all the industrial zones should have their own wastewater treatment stations, only about half of them (55.8%) obey the regulations, 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 a number of wastewater treatment plants, which have been inactive for 10 years. As another example, only 10% of the domestic wastewater and 30% of the one from local hospitals and manufactories in Hanoi are appropriately treated before discharging into water bodies. As for the results, the ESI of GSI_{132} is assessed at a very poor level of 0.16. Consequently, from the linear SIF case, the ESI of the management aspect is at the acceptable level of 0.47. This assessment makes sense not only in terms of environmental sustainability but also in a social point of view because as we explored via our social survey in 2014 that only 6% of respondents rating the government management at good level, more than half of them (51%) rating the performance at acceptable level (Bui et al., 2018). Generally, the ESI using the linear SIF, $\Omega_C(1)$ of groundwater in Hanoi is assessed at a good level of 0.66 (**Table 4-2**).

4.1.3.2 Combined Linear and Non-Linear SIFs

We continue to apply the linear SIF for the indicators of the management aspect (GSA_{13}) because the sustainability assessment based on the linear SIF seems to appropriately reflect the current management situation of the groundwater development in Hanoi.

However, in the quantity aspect, as mentioned previously in the sub-section 5.1, the ESIs based on the linear SIF of the indicator GSI_{111} is not suitable to reflect the "low" status of Hanoi groundwater development. So if the groundwater abstraction is 50% of the recharge (or the value of GSI_{111} is at $x_\alpha = 0.5$), its sustainability index α should be assessed at some values in the excellent sustainability range of 0.8 -1.0) (**Table 3-2**). This study hence roughly assumes 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 ($\alpha = 0.9$). The corresponding coefficients are calculated by using Eqs. (9), (10) & (11).

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

In addition for the quantity aspect, as mentioned in the previous sub-section 5.1, the indicators regarding groundwater depletion (declined groundwater level GSI_{113} and critical zone GSI_{114}) and its environmental impacts (land subsidence occurrence GSI_{115}) 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 to 0.2 (**Table 3-2**). We thus roughly take the judgment Eqs. (18) & (19) of ($\alpha = 0.1$ at $x_\alpha = 0.50$) for the critical zone indicator GSI_{114} of the quantity aspect GSA_{11}.

Table 4-2 Environmental sustainability assessment for Hanoi groundwater resources.

GSA	$W_A(i)$	GSI	$W_I(i,j)$	GSI value (x)	Linear SIF case Ω_I	Linear SIF case Ω_A	Linear SIF case Ω_C	Combined linear & non-linear SIF case Ω_I	Combined linear & non-linear SIF case Ω_A	Combined linear & non-linear SIF case Ω_C
Quantity (GSA_{11})	0.33	GSI_{111}	0.20	0.54	0.54	0.68 (Good)	0.66 (Good)	0.92	0.53 (Acceptable)	0.51 (Acceptable)
		GSI_{112}	0.20	0.87	0.87			0.87		
		GSI_{113}	0.20	0.81	0.81			0.43		
		GSI_{114}	0.20	0.77	0.77			0.35		
		GSI_{115}	0.20	0.42	0.42			0.07		
Quality (GSA_{12})	0.33	GSI_{121}	0.25	0.91	0.91	0.84 (Excellent)		0.68	0.52 (Acceptable)	
		GSI_{122}	0.25	0.85	0.85			0.51		
		GSI_{123}	0.25	0.70	0.70			0.26		
		GSI_{124}	0.25	0.90	0.90			0.64		
Management (GSA_{13})	0.33	GSI_{131}	0.33	0.63	0.63	0.47 (Acceptable)		0.63	0.47 (Acceptable)	
		GSI_{132}	0.33	0.16	0.16			0.16		
		GSI_{133}	0.33	0.63	0.63			0.63		

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

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

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. In order to have better assessment results, each indicator should be judged individually, however, as the first trial for Hanoi case study, we here also use Eqs. (18) & (19) for the declined level GSI_{113} and land subsidence occurrence GSI_{115} indicators.

Similar to the indicators of the quality aspect GSA_{12}, in order 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_{12} is needed. Regarding the area at risk of arsenic groundwater contamination, for example, if 50% ($x_\alpha = 0.5$) of Hanoi area are at risk of the contamination, its environmental sustainability index should be assessed at some values in the very poor range levels of 0 to 0.2 (**Table 3-2**). This study hence roughly assumes Eq. (18) condition, by which if 50% ($x_\alpha = 0.5$) of the areas are 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 apply Eq. (19) for other quality indicators regarding areas at risk of nitrogen, iron and manganese contamination of the quality aspect.

Using the same value x as shown in **Table 4-2**, we can get all the ESIs for GSI_{113}, GSI_{114}, GSI_{115} of the quantity aspect and for the four indicators in the quality aspect using Eqs. (17) & (19). The ESIs for Ω_A and the final ESI Ω_C are then calculated correspondingly by Eqs. (12) and (13). Those resulting sustainability indices are shown in the column for "Combined linear and non-linear SIF case" in **Table 4-2**. The results in this case are also visualized in **Fig. 4-1** as a solid line in the radar chart.

From the quantity aspect of **Table 4-2**, the indicator regarding abstraction-recharge relation is significantly improved to an excellent sustainability level of 0.92, 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_{113}, GSI_{114} and GSI_{115} in this quantity aspect are relatively reduced to poor 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 a sustainable groundwater development is to re-distribute appropriately the groundwater abstraction networks all over the area, by which, the groundwater abstraction could be increased immensely to utilize the natural rich recharge benefited from the local tropical climate features without making the current environmental adverse impacts resulted from groundwater over-exploitation and depletion more seriously. Consequently, ESI of the quantity aspect is appropriately assessed at an acceptable sustainability level of 0.53.

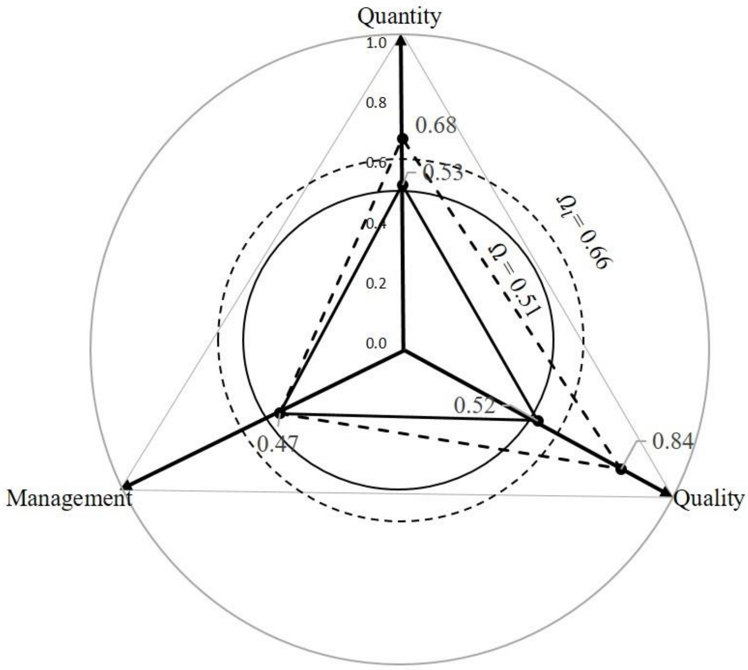

Fig. 4-1 Visualization of the environmental sustainability assessment results obtained by linear and the combined linear and non-linear SIF cases.

The sustainability indices for three aspects based on the linear SIF are shown as a 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.*

Similar to the quality aspect, all the indicators are significantly reduced, compared to those based on the linear SIF case. Specifically, the indicator related to metal contamination GSI_{123} is assessed at a poor sustainability level of 0.26, revealing the serious metal pollution in Hanoi groundwater recently. These assessments results for the quality aspect are appropriate to reflect the current quality situation (presented in the previous 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 a sustainability acceptable level of 0.52. 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 3-2**, 0.4 is the minimum sustainability index value in the acceptable sustainability range of 0.4 to 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.

$$\Omega_{I}\,(x_{\alpha} = 0.8) = 0.4 \tag{20}$$

Consequently, the final ESI, Ω_C for Hanoi groundwater is appropriately assessed at the acceptable level of 0.51 in this case (**Table 3**).

Fig. 4-1 clearly visualizes the difference in the sustainability assessment results between the linear and the combined linear and non-linear SIF cases. In terms of the assessment reflectivity to the actual situation, the sustainability assessment results based on the combined linear and non-linear SIF are more reasonable. The final ESI, Ω_C shows an environmentally acceptable overview of the sustainability of Hanoi groundwater development and management. It also indicates that improving the current quality and the strict enforcement of the environmental laws and regulations are the key processes for ensuring a feasibly sustainable groundwater resources in Hanoi.

4.2 Social Sustainability Assessment

Among three main pillars of sustainability concept, the social criterion has specifically received less consideration than the other economic and environmental criteria (Mani et al., 2016; Pinar et al., 2014; Vallance et al., 2011) because this concept is probably hard to define and quantify. There is no specific definition of social sustainability, so that 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 socially necessary conditions to support ecological sustainability and the equality requirement of rights of access to resources and social services. The meaning of the concept actually remains unclear, and more investigations are needed (Axelsson et al., 2013). As one of very few examples of the AHP applications on groundwater sustainability, Chen et al. (2015) deals with the assessment in the semiarid China Hohhot Plain region. In their study, the adopted indicators mainly focus on the environmental perspective, and the social perspective is almost neglected as the only one-indicator consideration of population density. There have been almost no studies dealing with the indicator-based AHP approach for groundwater sustainability assessment so far. Particularly for social sustainability assessment of groundwater, it is necessary to better understand the social demand and satisfaction of water usage as well as public attitudes toward a sustainable water resources management. Public responses and contribution 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.

4.2.1 Social Sustainability Aspects

In order to find the sustainability relevant issues, exploring carefully the current socially related problems of groundwater usage and regulations in the Hanoi communities is essential. In terms of social benefits, it is important to consider the social demand and satisfactory of the water 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 been presented in the literature. These problems obviously have an adverse impact on the community in both short and long terms, such that how to drive the Hanoi community toward sustainable development is 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, considerations of groundwater quantity, quality, and management concepts are considered three main social sustainability aspects as shown in **Table 4-3**. It is quite difficult to judge which aspect is more important to contribute to the final sustainability goal than the other aspect, so that in this study the main aspects are equally important.

4.2.2 Social Sustainability Indicators

Regarding development of a groundwater sustainability indicator, the UNESCO/IAEA/IAH Working Group first tried to define the sustainability indicators of groundwater resources that follow the DPSIR (Driving forces, Pressures, State, Impacts, and Societal Response) 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 mentioned how their indicator values positively or negatively affect three specific sustainable development criteria. Regarding groundwater quantity, for example, one indicator is defined as the ratio between groundwater abstraction and recharge. Physically, this ratio can be used as a sign of groundwater over-exploitation. In terms of benefits for society and economic development, the increase of groundwater abstraction is sufficient to meet the cumulative social demand. This increase, on the other hand, eventually has a series of adverse environmental and social impacts. It is apparently difficult to judge whether the increase of indicator values contributes positively or negatively to the specific sustainability criterion. It is, therefore, necessary to develop appropriate groundwater sustainability indicators from a particular criterion (social criterion in this case) to easily support this judgment. The social sustainability indicators are context-dependent and need to reflect the nature and requirements of the local community (McKenzie, 2004), so that the indicators should be selected and defined according to the current social problems of Hanoi groundwater.

Data is essential to develop integrated approaches for sustainable groundwater management (Rossetto et al., 2007). In a developing country like Vietnam, however, the data related to the sustainability of groundwater management is sparse, seldom systematically organized, and accessible to a very limited number of official users even though officials have been concerned with the sustainability concept for about ten years. In this study, we actually exerted much effort to gather the necessary data and more importantly to keep the data consistent. The primary data sets come 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 input data we used are authorized and reliable from our questionnaire survey in 2014, Ministry of Natural Resources and Environment in 2012, The Ministry of Science and Technology in 2017, and the biggest water company HAWACO in 2016 which is the government organization responsible for domestic and business water supply services in Hanoi. Regarding our questionnaire survey in 2014, 400 samples were collected from both urban and sub-urban districts in Hanoi. The survey purpose was to explore the public awareness of the current situation of water supply and groundwater resources, the water use habits and satisfactory of the water quantity, quality and management from 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 these data availability and reliability, the low reliability data (too old or from the unpublished works) were screen out, only the up-to-date, authorized and reliable data are selected for further indicator development as follows.

In terms of quantity aspect (GSA_{21}), which is the measure of social satisfaction with water use, we thus consider the following three sustainability indicators. The first indicator of this aspect, GSI_{211}, corresponds to the satisfactory 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 in the targeted area. Indeed, the terms "satisfaction" and/or "sufficient water use" are difficult to define because water sufficiency differs from region to region and person to person, depending on social needs and situation. As Vietnam is a developing country, we here define "minimum water satisfactory" as meaning people can use at least the average amount of water demanded in large Vietnamese cities (130 liters/capita/day) for their basic daily activities. The second indicator of the quantity aspect GSI_{212} represents the water restriction situation. In this study, in order to develop a positive correlation between indicator value and its social sustainability index (SSI), GSI_{212} is here 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 4-3**. Regarding the third indicator, $GSI_{213,}$ it is necessary to consider water accessibility. As defined by WHO (WHO, 2015), water accessibility is the presence of a water source nearby (within 500m) for use without considering safety, continuity, or quantity. The issue of this general water accessibility needs to be considered in the arid and semi-arid regions, but is not suitable for Hanoi due to its tropical monsoonal climate features. We thus consider the amount of time per day during the water restriction days that the community can access water from the water supply companies, which is named "24-hour water supply availability" for GSI_{213}. 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. Those indicators of the first aspect (GSA_{21}) and their index-based definitions are shown in **Table 4-3**.

In terms of quality aspect (GSA_{22}), which is the measure of social satisfaction with the water quality and degree of harm to human health. Due to the data availability and reliability, in this aspect we only consider the major groundwater problems in Hanoi to propose the indicators. In the literature of groundwater quality in Hanoi, it is recently concerned three major contamination agents of arsenic, nitrogen and coliform. So that for the quality aspect, three indicators needed to be considered to measure how much in percentage of the community is at risk of these three contamination agents. As guided by the UNESCO/IAEA/IAH, for example, the first indicator (GSI_{221}) of the quality aspect corresponds to arsenic contamination is defined as one minus the ratio of residents at risk of consuming the arsenic-contaminated groundwater to the total population. Furthermore, we consider an indicator measuring the actual health impact of the current water consumption. The fourth indicator (GSI_{224}) presents water-related diseases as a macro index.

Regarding the management aspect (GSA_{23}), we consider how the local government manages and improves the PWSS as the quality-controlled source 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 (GSI_{231}) refers to public water coverage. This indicator reflects how much the distribution network can reach the community. The second indicator (GSI_{232}) in this aspect is related to the PWSS capacity. This indicator refers to the balance between the water supply capacity of PWSS and the increasingly current demand resulting from the rapid urbanization in Hanoi. The third indicator (GSI_{233}) 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 its community in terms of budget allocation for the PWSS development. The fourth indicator (GSI_{234}) is a measure of water affordability which is defined as one minus the ratio of maximum water price to average household income. These four important indicators, GSI_{231}, GSI_{232}, GSI_{233}, and GSI_{234}, are government point of view. The fifth (GSI_{235}) and sixth (GSI_{236}) indicators present how the community responds to the current water conditions and regulations, which are mainly expressed by their willingness to pay for the PWSS improvement and willingness to participate in water-related programs.

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

4.2.3 Results and Discussion

According to the index-based definitions of the indicators described in the former section, we then calculated the indicator values, which are shown in **Table 4-4**. The following sub-sections explain how to get the social sustainability assessment results for Hanoi groundwater from both conventional linear relationship and non-linear SIF. Hereafter, the conventional relationship is expressed as the linear SIF.

4.2.3.1 The linear SIF case

In the case of the linear SIF in Eq. (6), each indicator value *x* is taken as its social sustainability index (SSI) Ω_I. The sustainability indices for Ω_A and the final social sustainability index Ω are calculated by Eqs. (12) and (13), respectively. The resulting sustainability indices are shown in the column for "Linear SIF case" in **Table 4-4**. In terms of quantity aspect (GSA_{21}), the indicator GSI_{211} is assessed at the excellent sustainability level of 0.98 according to the sustainability scale shown in **Table 3-2**, indicating that the majority of Hanoi communities can live off with the minimum water satisfactory of 130 liters/capita/day. The indicator GSI_{212} is assessed at the acceptable sustainability level of 0.55, suggesting that more than half of the communities have not suffered any water restriction situation. Lastly, the indicator GSI_{213} is also assessed at the acceptable sustainability level of 0.50, suggesting that water supply from PWSS is available for 12 hours per day even when the water restriction occurs. So that the SSI 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 appropriate to reflect the reality, because as we explored via our questionnaire survey, most of respondents agree that the PWSS recently has been improved pretty much from a quantity perspective.

Table 4-3 Social sustainability aspects and indicators for Hanoi groundwater resources

GSA	GSI	Consideration	Index-based definition
Quantity (GSA_{21})	GSI_{211}	Minimum water satisfactory	Ratio of residents who can use at least the Vietnamese unit water demand of 130liter/capita/day to the total population
	GSI_{212}	Water restriction	One minus the ratio of residents who have suffered water restriction in a target year to the total population
	GSI_{213}	24-hour water supply availability	Ratio of the average water accessed hours to 24 hours in the water restriction days of the target year
Quality (GSA_{22})	GSI_{221}	Arsenic contamination	One minus the ratio of residents who have risk of consuming the groundwater arsenic contamination to the total population
	GSI_{222}	Nitrogen contamination	One minus the ratio of residents who have risk of consuming the groundwater nitrogen contamination to the total population
	GSI_{223}	Coliform contamination	One minus the ratio of residents who have risk of consuming the groundwater coliform contamination to the total population
	GSI_{224}	Water-related diseases	One minus the ratio of residents who have water-related diseases to the total population
Management (GSA_{23})	GSI_{231}	Public water coverage	Ratio of the coverage from the public water distribution network
	GSI_{232}	Water work capacity	Ratio of water supply capacity to demand
	GSI_{233}	Annual investment	Ratio of the annual investment in water supply per capital to the required unit costs for water supply facilities
	GSI_{234}	Water affordability	One minus the ratio of the maximum water prices to the average capita income
	GSI_{235}	Willingness to pay	Ratio of residents are willing to pay for improving the water supply system to the total population
	GSI_{236}	Willingness to participate	Ratio of residents who are willing to participate in any water conservation and protection activities to the total population

Similarly, in terms of quality aspect (GSA_{22}), GSI_{221} and GSI_{222} indicators regarding arsenic and nitrogen contamination are assessed at the acceptable sustainability level. GSI_{223} related to coliform contamination is assessed at the good sustainability level. As a macro index, the GSI_{224} indicator concerning water-related disease is assessed at the excellent sustainability level, so that the sustainability index of the quality aspect is assessed at a good sustainability level of 0.66. From the quality point of view as described in the study area, however, only half of Hanoi's population accessed PWSS, which provides the quality-controlled water source (HAWACO, 2014). That means the other half is still using the quality-uncontrolled water source that can be dangerous to human health in case of contamination. Actually, the indicator GSI_{221}, 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 groundwater and its adverse human health impacts in Hanoi and RRD in the literature; Hanoi government is trying hard not only to control the ever-increasing groundwater abstraction but also raise the public awareness of this serious situation via their various communication media. The communities are recommended to use the advanced water purifiers in the urban districts and the sand filter arsenic removal technique in the sub-urban districts before use for domestic purposes. Where the sustainable society is concerned, therefore, the SSI of this indicator should be naturally assessed at the very poor sustainability level. Based on the linear SIF, however, the sustainability index of GSI_{221} is assessed as socially acceptable of 0.44, which is inappropriate to reflect the severe problems in Hanoi regarding arsenic groundwater pollution situation. Therefore, there is a gap between the social sustainability assessment and its reflectivity of actual quality groundwater problems in Hanoi.

In terms of management aspect (GSA_{23}), four of six indicators, GSI_{231}, GSI_{232}, GSI_{233}, and GSI_{234}, are assessed at from the good to excellent sustainability levels, showing that not only the PWSS can cover more than two-thirds of Hanoi communities but also its capacity mostly meet 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, Hanoi government recently gives much attention to reduce the high pressure on groundwater resources by financing a number of water treatment plants which take surface water from rivers in and nearby the capital. The investment indicator (GSI_{233}) is thus assessed at good level of 0.63 but it is still not enough to meet the communities' expectation; it is as a usual condition of a developing country. In order to find out the immense financial sources, the big efforts should come from both government and community sides.

At the management side, reducing the complexity of current regulations and policies and increasing international collaboration opportunities are highly recommended to attract more external financial sources. Along with that, it is also important to encourage the supports from the local communities. At the community side, being actively improve the current poor awareness of clean water and using it efficiently are crucial. Regarding the limited public awareness of water issues, furthermore, the index for GSI_{236} is almost reaching the poorest sustainability level, most of them are not willing to participate in any water-related program which is supposed to be able to broaden up the public understanding and awareness of safe water sources. This assessment appropriately reflects the unawareness stage of the majority of local communities. However as shown in GSI_{235}, more than half (56%) of the communities are desired to contribute their financial assistances to support PWSS improvement projects, means that the majority of them accepted to pay a higher water prices if the PWSS will be more improved. Therefore, resulting 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_l of Hanoi groundwater is assessed at a good sustainability level of 0.65 (**Table 3-2**).

4.2.3.2 The combined linear and non-linear SIF case

We keep applying the linear SIF for the indicators of the quantity aspect (GSA_{21}) because the sustainability assessment based on the linear SIF seems to be appropriate to reflect the current quantity situation of the water use in Hanoi.

In terms of quality aspect, as mentioned previously in the sub-section **4.2.3.2**, the sustainability indices based on the linear SIF are not appropriate to reflect the serious situation of groundwater quality problems in Hanoi. So that, regarding to the risk of arsenic groundwater contamination, for example, if 50% ($x_\alpha = 0.5$) of the communities are at risk of the contamination, the SSI in this case should be assessed at some values in the very poor range levels of 0 to 0.2 (**Table 3-2**). This study hence roughly assumes the following condition (Eq. 21), by which if 50% ($x_\alpha = 0.5$) of the communities are at this risk of arsenic groundwater contamination, sustainability will be assessed at very poor value of 0.1 ($\alpha = 0.1$).

$$\Omega_I\,(x_\alpha = 0.5) = 0.1 \qquad (21)$$

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. In order to have a better assessment results, each indicator should be judged individually, however, as the first trial for Hanoi case study, we here also use Eq. (21) for the indicators regarding nitrogen, coliform contamination risk and the health impacts of the quality aspect (GSA_{22}). We then obtain the following Eq. (22) for sustainability index evaluations of the four quality sustainability indicators.

$$\Omega_I\,(x) = 0.0125e^{4.3944x} - 0.0125 \qquad (22)$$

For the management aspect GSA_{23}, other than the water affordability indicator GSI_{234}, the assessments resulted from the linear SIF seem to be appropriate. GSI_{234} is one of the interesting indicators in this aspect because it shows up exactly how the government controls the water price 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 U.S. Environmental Protection Agency (U.S. EPA)'s affordability criteria, which indicates that the water bill is affordable if it constitutes less than 2.5% of the median household income. Actually, in family and city scales, the price of water supply even somehow reaches 28% of the average monthly income (Lucía et al., 2017): \$104 in Hanoi (UNDP, 2010); it is more than ten times higher than the U.S. EPA affordability criterion. It shows evidently how hard it is for the communities every single day using the safe water from PWSS. The safe water is physically available, but economically unreachable for living. So that it is necessary to apply the non-linear SIF to assess the sustainability of the water affordability indicator. The water bill is reaching 28% in this case, the sustainability index should be assessed at some values in the poor range of 0.2 to 0.4, or even in the very poor range of 0 to 0.2. We thus roughly take the judgment Eq. (15) of (α = 0.2 at x_α = 0.72) for the affordability indicator GSI_{234} of the management aspect GSA_{23}.

$$\Omega_I\,(x_\alpha = 0.72) = 0.2 \tag{23}$$

Using the same value *x* as shown in **Table 4-4**, we can get all the sustainability indices for all the indicators of the quality and GSI_{234} of the management aspects using Eqs. (22) and (23). The sustainability indices for Ω_A and the final social sustainability index Ω are then calculated correspondingly by Eqs. (11) and (12). Those resulting sustainability indices are also shown in the column for "Combined linear and non-linear SIF case" in **Table 4-4**. The results in this case are also visualized in **Fig. 4-2** as a solid line in the radar chart.

From **Table 4-4**, all the social sustainability indices Ω_I of the indicators of quality aspect are significantly reduced, compared to those based on the linear SIF. The sustainability indices of the two indicators GSI_{221} and GSI_{222} are reduced to very poor sustainability level, and GSI_{223} 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 good to poor level of 0.27. These assessments results for the quality aspect and its indicators are appropriate to reflect the current situation because about one-third of Hanoi communities are dissatisfied and complained on the water quality based on the results from our 2014 questionnaire survey. There is also existed a series of adverse impacts on social and environmental conditions of groundwater over-exploitation and contamination (Berg et al., 2008; Bui et al., 2012b). The communities also know about this serious situation via various media, but they have no better choices other than using the current water sources.

For the indicator GSI_{234} of the management aspect, the sustainability index is drastically reduced to the poor level, it seems to be reflect well the unbalanced condition between the average low incomes of a part of communities and the relatively high water price. 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 that only 6% of respondents rating the government management at good level, more than half of them (51%) rating it at acceptable level.

Consequently, the final SSI Ω for Hanoi groundwater is appropriately assessed at the acceptable level of 0.49 in this case (**Table 4-4**). **Fig. 4-2** clearly visualizes the difference in the sustainability assessment results between the linear and the combined linear and non-linear SIF cases. In terms of the assessment reflectivity to the actual situation, the sustainability assessment results based on the combined linear and non-linear SIF are more reasonable.

Table 4-4 Social sustainability assessment for Hanoi groundwater resources.

GSA	$W_A(i)$	GSI	$W_I(i,j)$	Indicator value (x)	Linear SIF case			Combined linear & non-linear SIF case		
					Ω_I	Ω_A	Ω_C	Ω_I	Ω_A	Ω_C
Quantity (GSA_{21})	0.33	GSI_{211}	0.33	0.98	0.98	0.68 (Good)	0.65 (Good)	0.98	0.68 (Good)	0.49 (Acceptable)
		GSI_{212}	0.33	0.55	0.55			0.55		
		GSI_{213}	0.33	0.50	0.50			0.50		
Quality (GSA_{22})	0.33	GSI_{221}	0.25	0.44	0.44	0.66 (Good)		0.07	0.27 (Poor)	
		GSI_{222}	0.25	0.57	0.57			0.14		
		GSI_{223}	0.25	0.78	0.78			0.37		
		GSI_{224}	0.25	0.85	0.85			0.34		
Management (GSA_{23})	0.33	GSI_{231}	0.17	0.68	0.68	0.60 (Good)		0.68	0.52 (Acceptable)	
		GSI_{232}	0.17	0.87	0.87			0.87		
		GSI_{233}	0.17	0.63	0.63			0.63		
		GSI_{234}	0.17	0.72	0.72			0.20		
		GSI_{235}	0.17	0.56	0.56			0.56		
		GSI_{236}	0.17	0.15	0.15			0.15		

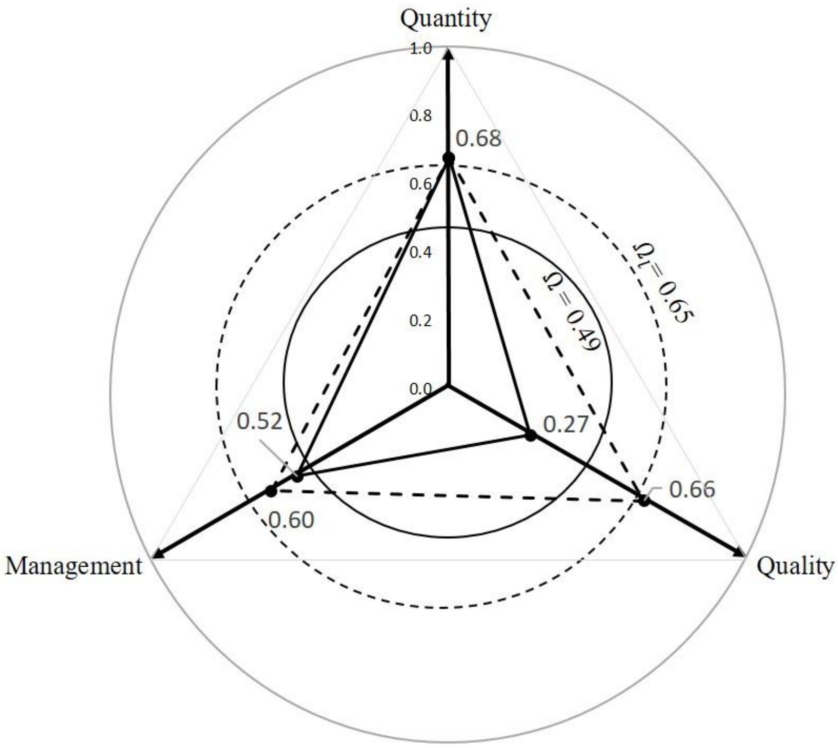

Fig. 4-2 Visualization of the social sustainability assessment results obtained by linear and the combined linear and non-linear SIF cases.

The social sustainability indices for three aspects based on the linear SIF are shown as a 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 social 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*.

4.3 Economic Sustainability Assessment

"Act locally", but need to "think globally". This concept has been critically emphasized for any economic sector to ensuring sustainable development of communities, cities, and countries. Water resources development is nowadays getting more attention from both researchers and practitioners worldwide because 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).

In Hanoi, Vietnam, groundwater resources is the most important water supply sources (accounting 93% of domestic water use contribution (Hawaco, 2014)), for the communities here where most of the rivers and lakes here are seriously polluted due to the discharge of untreated industrial, agricultural, aquacultural and domestic waste (Bui et al., 2012a). The resource also significantly contributes to Hanoi industrial and service sectors with a high proportion of 77% (MONRE, 2016). Unfortunately, this groundwater recently become seriously degraded in both quantity and quality perspectives due to the rapid exploitation of the groundwater without an appropriate management. From a quantity point of view, the aquifer system and groundwater potential resources for Hanoi was explored (Bui et al., 2012a) and the whole RRD (Red River Delta) where Hanoi is located (Bui et al., 2011) but also evidently showed the seriously declining groundwater levels in Hanoi central areas (Bui et al., 2012b). From a quality point of view, the hydrogeochemical characteristics of groundwater in Hanoi and the RRD were investigated (Nguyen et al., 2014; Nguyen et al., 2015a), crucially supporting the hydrogeochemical assessment of groundwater quality during dry and rainy seasons for this target area and the whole RRD (Nguyen et al., 2015b; Nguyen et al., 2015c) . As for the results of a series of Hanoi groundwater quality assessment studies, the groundwater resource has been locally contaminated mainly by arsenic, coliform and nitrogen (Berg, et al., 2001; 2008; Bui et al., 2007). These serious quantity and quality degradations require a certain budget for groundwater abstraction, appropriate treatment and long-term remediation, thus threatening the community's goal of sustainable groundwater development.

Therefore, it is necessary to measure sustainability of Hanoi groundwater resources. As one of the developing countries, economic benefits and development in Vietnam are always put at higher priorities compared to two other sustainable development goals (social and environment (Brundtland, 1987)).

Currently, up to 632,172 m^3/day of groundwater is exploited for water supply purpose (MONRE, 2016). Hanoi government now is trying to reduce this pressure on groundwater abstraction by establishing several surface water treatment plants to use the water resources from rivers in Hanoi and nearby. Hanoi groundwater not only contribute to domestic water use but also contribute to industrial and service. According to Ministry of Natural Resources and Environment (MONRE, 2016), approximately 693,572.7 m^3/day of groundwater is abstracted for industrial and service purposes; expecting that the industrial water demand will be about 82,000 m^3/day in 2020 (No.499/QD-TTg, March 21, 2013). According to Hanoi Water Limited Company (HAWACO, 2014), the largest water distribution company in Hanoi, 55% of the city's population, or 3.6 million users, have access to public water system, 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 their private and community wells in 2010 without any quality standard (UNDP, 2010). The reason for this unreliable water use manner is due to not only the unstable water supply quantity but also their low monthly incomes compared to the monthly water bills (Lucia et al., 2017).

4.3.1 Economic sustainability aspects and indicators

For economic sustainability assessment, the context of quantity, quality, and management are also considered as the three main economic sustainability aspects. The indicators in these aspects are developed by referring to indicator establishment from the UNESCO/IAEA/IAH Working Group, this study is an attempt to design and customize the most useful indicators based on local groundwater issues in Hanoi.

As mentioned in **Chapter 2**, Hanoi groundwater not only contribute to domestic water use but also contribute to industrial and commercial purposes. It is apparently important to consider how much groundwater contributes to these economic sectors of Hanoi economic development from quantity aspect. So that for quantity aspect (GSA_{31}), the indicator GSI_{311} shows the proportion of groundwater contributed to domestic water use purpose; GSI_{312} demonstrates the proportion of groundwater contributed to industrial and commercial purposes. For the third indicator, GSI_{313} is a measure of how much water supply which is efficient for use. The reason is that even the excessive groundwater abstraction has caused serious groundwater-level declines, the public water utilities failed to supply urban districts approximately every two days per month (HAWACO, 2016). The water loss is reported at the high rate of 38% in

Hanoi due to the inappropriate pipe system (ADB, 2010). By these index-based definitions, the indicator values are in the range of zero to one. Those indicators of the first aspect (GSA_{31}) and their index-based definitions are shown in **Table 4-5.**

From a quality point of view, as mentioned in Hanoi groundwater situation literature review, the resource is seriously polluted. Thus it is important to consider how much monetary need is looked-for groundwater remediation (GSI_{21}) because groundwater contamination is extremely expensive to remediate. GSI_{321} in this case is defined as one minus the ratio of the remediation cost for groundwater contamination to Hanoi GDP on average to make the positive relation between indicator value and its sustainability index. For the second indicator of quality aspect, according to Economics of Sanitation Initiative of Water and Sanitation Program of World Bank (World Bank, 2012), 260 million USD is estimated for Vietnam economic loss because the communities' health problems are closely related to the low-quality water use. So here how much the communities need to pay for their water–related disease treatment (GSI_{322}) is considered. GSI_{322} is also defined as one minus the ratio of the estimated loss from water-related diseases to Hanoi GDP in a target year. These indicators are important in terms of groundwater quality because the demand for clean and safe water has become urgent not only in Vietnam but also in all developing countries (JICA, 2016).

Water resources development is derived and controlled by the local government and communities. Regarding government side, this study here considers how local government manages and improves the public water supply as the stable quantity and controlled quality sources for the community. Based on the current eco-social situation, the first indicator (GSI_{331}) refers to public water coverage. This indicator reflects how much the distribution network can reach the community. The second indicator (GSI_{332}) in this aspect is related to the annual investment per capita compared to the required unit cost for water supply facilities. This indicator shows how much the government cares about water resources development sector in terms of budget allocation. Regarding the community side, it is also necessary to consider how the community responds to the management and water-related policies, and how ready the community is for better water supply. So that the indicator GSI_{333} is a measure of how the current water is affordable or cheap enough compared to the average household income of the communities. Because the maximum water prices is somehow reaching 28% of the average income of Hanoi's population, considering 104.00 USD per month (UNDP, 2010). This water price-income relation apparently causes pretty much difficulty for the households whether they want to use the better quality water sources. For the last indicator in the community side, the GSI_{334} is defined as the ratio of residents' willingness to pay for improving the water supply system to their current water bills. GSI_{334} thus shows not only the degree of public awareness but also how ready the communities are for a better quality water use (**Table 4-5**).

Finally, three main sustainability aspects (quantity, quality and management) and their respectively three, two and four corresponding GSIs are proposed and defined to build up the economic sustainability hierarchy for Hanoi groundwater mainly based on the current problem consideration (**Table 4-5**).

4.3.3 Results and Discussion

After the weights for the aspects and indicators are obtained from Eqs. (1) and (2), the sustainability indices for $\mathbf{\Omega}_A$ and the final economic sustainability index (CSI) Ω are calculated by Eqs. (5) and (6), respectively. Those resulting sustainability indices are shown in **Table 4-6** and their visualization is shown in **Fig. 4-3**.

Table 4-5 Economic sustainability aspects and indicators for Hanoi groundwater resources.

GSA	GSI	Consideration	Index-based definition	Benefit/Cost
Quantity (GSA_{31})	GSI_{311}	Domestic water use contribution	Groundwater as a percentage of the Hanoi total water use for domestic purpose	Benefit
	GSI_{312}	Industrial and commercial water use contribution	Groundwater as a percentage of the Hanoi total water use for industrial purpose	Benefit
	GSI_{313}	Effective water supply	Effective water supply as a percentage of the total water supply	Benefit
Quality (GSA_{32})	GSI_{321}	Groundwater remediation cost	One minus the ratio of the remediation cost for GW contamination to Hanoi GDP on average	Cost
	GSI_{322}	Water-related disease cost	One minus the ratio of the estimated loss from water-related diseases to Hanoi GDP on average	Cost
Management (GSA_{33})	GSI_{331}	Public water coverage	Ratio of the coverage from the public water distribution network	Benefit
	GSI_{332}	Investment	Ratio of the annual investment in water supply per capita to the estimated unit costs for water supply facilities	Benefit
	GSI_{333}	Affordable water	One minus the ratio of the average water prices to the average capital income	Benefit
	GSI_{334}	Willing payability	Ratio of the average household willingness to pay for improving the water supply system to their average water bill per month	Benefit

4.3.3.1 The linear SIF case

In terms of quantity aspect (GSA_{31}), the indicator GSI_{311} is assessed at the excellent sustainability level of 0.930 according to the sustainability scale shown in **Table 3-2**, indicating that Hanoi domestic water supply almost completely depends on groundwater resources abstraction. The groundwater also significantly contribute to the water consumption of industrial and commercial activities with a good CSI of 0.770. These evaluations reveal the vital role of groundwater resources in Hanoi economic development. The indicator GSI_{313} is assessed at the good sustainability level of 0.62, indicating that 38% of the water supply ineffectively reaches the water users. The total capacity of all the water supply companies in HAWACO is 534,500 m^3/day (HAWACO, 2016), so that the economic loss due to this ineffective water supply is approximately estimated as 1.6 billion VND/day (about 70,000USD/day at the current rate of (1 USD = 22,767VND) and water price of 8,000VND/m^3). The estimated economic loss due to the ineffective water supply is considerable. Consequently, the good sustainability level is economically assessed for the quantity aspect with the index $\Omega_A(1)$ of 0.773 (**Table 4-6** and **Fig. 4-3**).

Similarly, in terms of quality, GSI_{321} and GSI_{322} indicators regarding groundwater remediation and water–related disease costs are assessed at the good and even excellent economic sustainability levels of 0.740 and 0.998, respectively. These economic sustainability indices show that the economic loss due to the adverse impacts of contaminated groundwater to human health are negligible for a short term consideration (in this case, a year as the index-based definitions for GSI_{321} and GSI_{322}). However, the groundwater is seriously polluted in the literature and it was estimated that 10 million people in the Red River Delta where Hanoi is located are affected due to arsenic exposure (Berg et al., 2001) for instance. Therefore, these economic sustainability assessments suggest that GSA_{32} should be considered in a long term period to see more appropriately how significant the economic loss will be due to the currently severe groundwater contamination in Hanoi. The quality aspect is economically assessed at the excellent level (**Table 4-6** and **Fig. 4-3**).

In terms of management aspect (GSA_{33}), all indicators are assessed at good and even excellent sustainability level. The indicator GSI_{331} shows that the public water system cover about two-thirds of Hanoi communities. The investment indicator GSI_{332} is assessed at good economic sustainability level, which reveal that Hanoi government recently gives much attention to increase their budget allocation for water supply improvement. In a number of households, more than one-tens (15%) as the average monthly incomes are spent for water consumption based on the assessment of the indicator GSI_{333}. In comparison with the "water bill-average household income" percentages in Japan of 0.15%, and in United Kingdom and Wales of 1.50% in 2016 (City-Cost, 2017; Water UK, 2018), it is quite difficult for a part of Hanoi communities to afford for their monthly water bills based on their own incomes. The last indicator, GSI_{334} is economically assessed at good level of 0.670 indicating that 58% (as the results from the survey in 2017) of the communities are willing to pay more than half of their current water bills for a better water use condition. This is a positive signal from the communities for implementation of water supply improvement projects. As a result, the economic sustainability index of the management aspect is assessed at the good level of 0.708.

Consequently, the CSI, Ω of Hanoi groundwater is assessed at a good sustainability level of 0.783 (**Table 3-2**). In **Fig. 4-3**, the economic sustainability indices for the three aspects are shown as a solid line triangle in the radar chart. The final economic sustainability index **Ω** is also shown as the solid line circle with the radius equal to **Ω** value.

4.3.3.2 The combined linear and non-linear SIF case

As mentioned in the previous sub-section **4.3.3.1**, the economic sustainability indices assessed for GSI_{313} and GSI_{333} are not suitable to reflect well the actual situation.

For the former indicator, regarding the ineffective water supply, for example, if a half ($x_{\alpha} = 0.5$) of the water supply are waste, its economic sustainability index should be assessed at some values in the very poor range levels of 0 to 0.2 (**Table 3-2**). This study hence roughly assumes the condition (Eq. 21), by which if 50% ($x_\alpha = 0.5$) of the water supply does not reach the water users, its sustainability will be assessed at very poor value of 0.1 (α = 0.1). Similarly, Eq. (22) are obtained and applied for sustainability index evaluation of the GSI_{313}. Therefore, in this case, the economic sustainability index of GSI_{313} is assess at a very poor level of 0.18. For the latter indicator, similarly in the social sustainability assessment of the management aspect, GSI_{333} is necessary to be applied the non-linear SIF to assess the sustainability. The water bill is reaching 15% in this case, the sustainability index is also assessed roughly at 0.2.

Using the same value x as shown in **Table 4-4**, we can get all the sustainability indices for all the indicators. The sustainability indices for Ω_A and the final social sustainability index Ω are then calculated correspondingly by Eqs. (11) and (12). Those resulting sustainability indices are also shown in the column for "Combined linear and non-linear SIF case" in **Table 4-6**. The results in this case are also visualized in **Fig. 4-3** as a solid line in the radar chart. Similarly to the environmental and social sustainability assessment cases, the economic sustainability indices of the quantity and management aspects are reduced appropriately. Therefore, the final economic sustainability index is also reduced to 0.68. **Fig. 4-3** clearly visualizes the difference in the sustainability assessment results between the linear and the combined linear and non-linear SIF cases. In terms of the assessment reflectivity to the actual situation, the sustainability assessment results based on the combined linear and non-linear SIF are more reasonable.

Table 4-6 Economic sustainability assessment for Hanoi groundwater resources.

GSA	$W_A(i)$	GSI	$W_I(i,j)$	Indicator value (x)	Linear SIF case			Combined linear & non-linear SIF case		
					Ω_I	Ω_A	Ω_C	Ω_I	Ω_A	Ω_C
Quantity (GSA_{31})	0.33	GSI_{311}	0.33	0.93	0.93	0.77 (Good)	0.78 (Good)	0.93	0.63 (Good)	0.68 (Good)
		GSI_{312}	0.33	0.77	0.77			0.77		
		GSI_{313}	0.33	0.62	0.62			0.18		
Quality (GSA_{32})	0.33	GSI_{321}	0.50	0.74	0.74	0.87 (Excellent)		0.74	0.87 (Excellent)	
		GSI_{322}	0.50	0.99	0.99			0.99		
Management (GSA_{33})	0.33	GSI_{331}	0.25	0.68	0.68	0.71 (Good)		0.68	0.55 (Acceptable)	
		GSI_{332}	0.25	0.63	0.63			0.63		
		GSI_{333}	0.25	0.85	0.85			0.20		
		GSI_{334}	0.25	0.67	0.67			0.67		

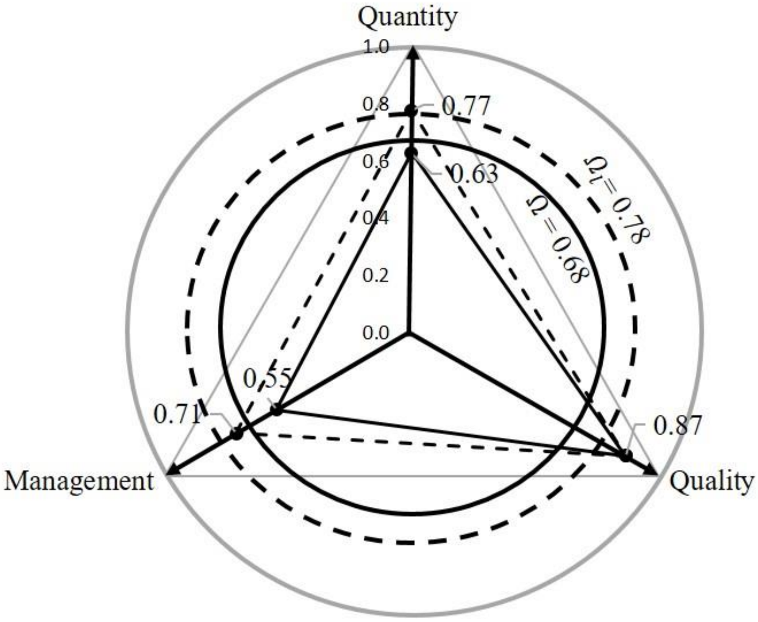

Fig. 4-3 Visualization of the economic sustainability assessment results obtained by linear and the combined linear and non-linear SIF cases.

The sustainability indices for three aspects based on the linear SIF are shown as a dashed line triangle; the final economic 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 economic sustainability index* Ω *in this case is shown as the solid line circle with the radius equal to* Ω *value.*

4.4 All-purpose Groundwater Sustainability Assessment

Regarding the AHP sustainability assessment application of groundwater resources, there have been very few intensive studies dealing with the groundwater resources in Hohhot Plain in China as one of the very few examples investigated in the semiarid regions where the annual precipitation is about 408 mm only (Chen et al., 2015). There have been no such studies carried out in Vietnam's groundwater resources as a representative of tropical monsoonal areas in the AHP sustainability literature. This research, for the first time, thus assesses groundwater sustainability of Hanoi by applying the proposed AHP-SAG, all the three main pillars (environmental, social and economic) of sustainability concept were considered as the three important sustainability criteria in the framework. It is apparent that it is difficult to judge which

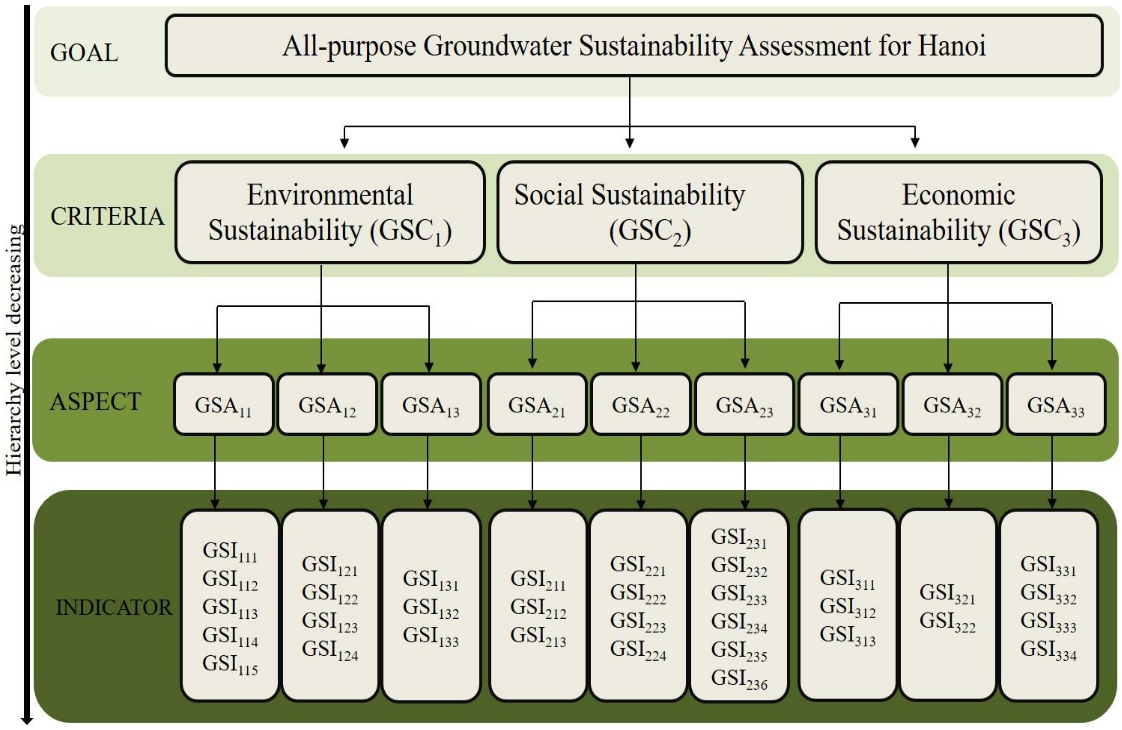

Fig. 4-4. All-purpose Groundwater Sustainability Assessment Framework for Hanoi.

criterion is more important than another criterion to contribute to the final groundwater sustainability goal than the other criteria, so that in this study the three GSCs are equally important. Based on the available and reliable data of the current groundwater situation in the target area, the sustainability aspects were proposed as quantity, quality, and management in each criterion. Furthermore, the sustainability indicators in each aspect were defined clearly in the previous sub-section **4.4.1**; **4.4.2**; **4.4.3**. Finally, the environmental, social and economic criteria were composed of their twelve, thirteen and nine core sustainability indicators, respectively, which could present the overall situation of groundwater resources development in Hanoi. The all-purpose groundwater sustainability assessment framework is summarized in the **Fig. 4-4**. For the all-purpose groundwater sustainability index (Ω) evaluation, the actual values of all the GSIs are the same with the ones in the previous subsections of environmental, social and economic sustainability assessment. Hence, Ω is calculated by Eq. (14). The results of the all-purpose index evaluations are presented in **Table 4-7**.

Table 4-7 All-purpose groundwater sustainability assessment for Hanoi

GSC	GSA	GSI	Linear SIF case				Combined linear & non-linear SIF case			
			Ω_I	Ω_A	Ω_C	Ω	Ω_I	Ω_A	Ω_C	Ω
GSC_1	Quantity (GSA_{11})	GSI_{111}	0.54	0.68 (Good)	0.66 (Good)	0.70 (Good)	0.92	0.53 (Acceptable)	0.51 (Acceptable)	0.56 (Acceptable)
		GSI_{112}	0.87				0.87			
		GSI_{113}	0.81				0.43			
		GSI_{114}	0.77				0.35			
		GSI_{115}	0.42				0.07			
	Quality (GSA_{12})	GSI_{121}	0.91	0.84 (Excellent)			0.68	0.52 (Acceptable)		
		GSI_{122}	0.85				0.51			
		GSI_{123}	0.70				0.26			
		GSI_{124}	0.90				0.64			
	Management (GSA_{13})	GSI_{131}	0.63	0.47 (Acceptable)			0.63	0.44 (Acceptable)		
		GSI_{132}	0.16				0.16			
		GSI_{133}	0.63				0.63			
GSC_2	Quantity (GSA_{21})	GSI_{211}	0.98	0.68 (Good)	0.65 (Good)		0.98	0.68 (Good)	0.49 (Acceptable)	
		GSI_{212}	0.55				0.55			
		GSI_{213}	0.50				0.50			
	Quality (GSA_{22})	GSI_{221}	0.44	0.66 (Good)			0.07	0.27 (Poor)		
		GSI_{222}	0.57				0.14			
		GSI_{223}	0.78				0.37			
		GSI_{224}	0.85				0.34			
	Management (GSA_{23})	GSI_{231}	0.68	0.60 (Good)			0.68	0.52 (Acceptable)		
		GSI_{232}	0.87				0.87			
		GSI_{233}	0.63				0.63			
		GSI_{234}	0.72				0.20			
		GSI_{235}	0.56				0.56			
		GSI_{236}	0.15				0.15			
GSC_3	Quantity (GSA_{31})	GSI_{311}	0.93	0.77 (Good)	0.78 (Good)		0.93	0.63(Good)	0.68(Good)	
		GSI_{312}	0.77				0.77			
		GSI_{313}	0.62				0.18			
	Quality (GSA_{32})	GSI_{321}	0.74	0.87 (Excellent)			0.74	0.87 (Excellent)		
		GSI_{322}	0.99				0.99			
	Management (GSA_{33})	GSI_{331}	0.68	0.71 (Good)			0.68	0.55 (Acceptable)		
		GSI_{332}	0.63				0.63			
		GSI_{333}	0.85				0.20			
		GSI_{334}	0.67				0.67			

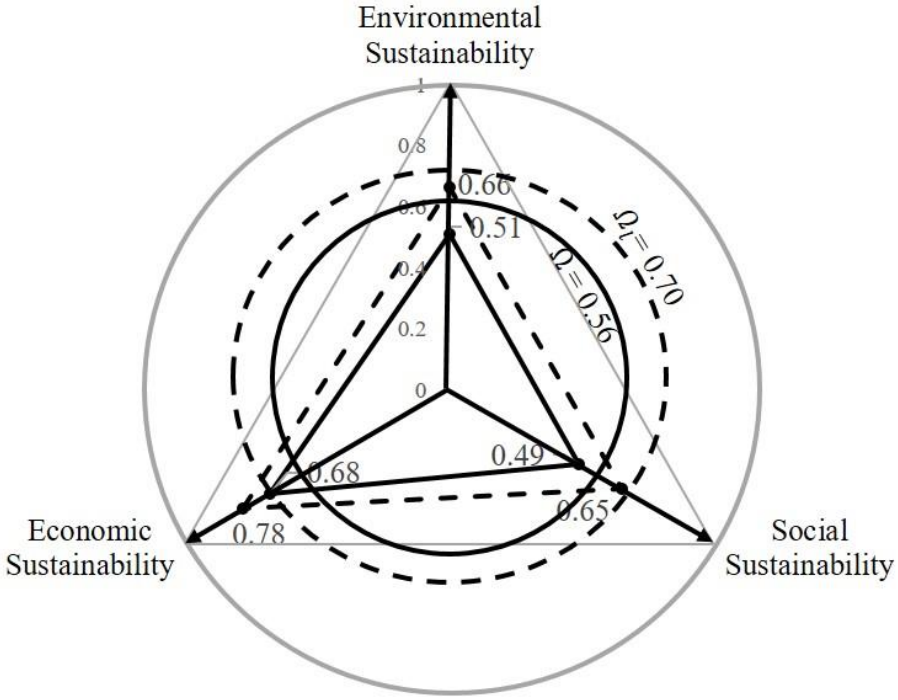

Fig. 4-5 Visualization of the all-purpose groundwater sustainability assessment results obtained by linear and the combined linear and non-linear SIF cases.

The sustainability indices for three criteria based on the linear SIF are shown as a dashed line triangle; the all-purpose 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 criteria based on the combined linear and non-linear SIFs are shown as a solid line triangle; the all-purpose sustainability index* Ω *in this case is shown as the solid line circle with the radius equal to* Ω *value.*

From the results presented in **Table 4-7**, the environmental, social and economic criteria were composed of their twelve, thirteen and nine (34 in total) core sustainability indicators, respectively. By gathering the necessary data, environmental, social and economic sustainability assessment of Hanoi was investigated by using the proposed AHP-SAG. It was found that the sustainability indices assessed by the combined linear and non-linear SIF case were more reasonable than the conventional linear SIF alone because the sustainability indices properly reflected the current groundwater problems in Hanoi. The environmental, social and economic criteria were appropriately assessed at acceptable, acceptable, and good sustainability levels, respectively. Lastly, the all-purpose groundwater sustainability index was assessed at acceptable level. **Fig. 4-5** visualizes the all-purpose groundwater sustainability assessment results obtained by linear and the combined linear and non-linear SIF cases. Finally, Ω is assessed at a good level of 0.70 based on the linear SIF and is appropriately reduced to an acceptable level of 0.56 in the combined linear and non-linear SIF case.

However, there was a big variation of the thirty four sustainability index values for these indicators (**Fig. 4-6**). Some indicators (GSI_{115}, GSI_{132}, GSI_{221}, GSI_{222}, GSI_{236} and GSI_{313}) were assessed closely to the poorest (or falling into Zone (I) of the very poor sustainability levels) while the others (GSI_{111}, GSI_{121}, GSI_{124}, GSI_{211}, GSI_{311} and GSI_{322}) were even reaching the most excellent sustainability levels (or falling into Zone (V) of the excellent sustainability levels). The big variability is not only shown in the whole, but also in each criterion, in which, the variability among the CSIs is the biggest, compared to ESIs and SSIs. Mostly the ESIs and SSIs of indicators fall into Zone (II), (III), and (IV) while the majority of CSIs are falling into Zone (IV) of the good sustainability levels. The results implies that groundwater resources has a significant contribution to Hanoi economic development, however, an appropriate management system is required to ensure the sustainability of both environmental and social performances.

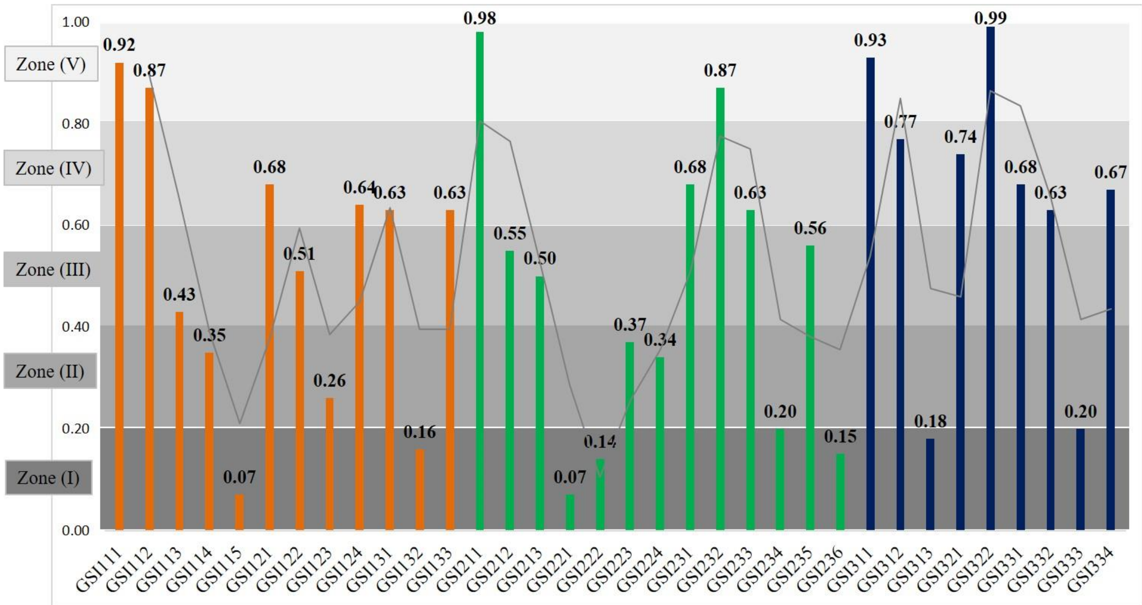

Fig. 4-6 Variability of the sustainability index values of indicators by the combined linear and non-linear SIF case.

Zones (I), (II), (III), (IV), and (V) indicate the sustainability scales of very poor, poor, acceptable, good and excellent ranges, respectively. The ESIs, SSIs, and CSIs are correspondingly shown in yellow, green and blue columns.

4.5. Conclusion

This chapter dealt with the applications of the proposed AHP-SAG technique in sustainability assessment of groundwater resources in Hanoi, in which all the three main pillars (environmental, social and economic) of sustainability concept were considered as the three important sustainability criteria in the framework. Based on the available and reliable data of the current groundwater situation in the target area, the sustainability aspects were proposed as quantity, quality, and management in each criterion. Furthermore, the sustainability indicators in each aspect were defined clearly, which could present the overall situation of groundwater resources development in Hanoi.

For sustainability assessment, the environmental, social and economic criteria were composed of their twelve, thirteen and nine core sustainability indicators, respectively. By gathering the necessary data, environmental, social and economic sustainability assessment of Hanoi was investigated by using the proposed AHP-SAG. It was found that the sustainability indices assessed by the combined linear and non-linear SIF case were more reasonable than the conventional linear SIF alone because the sustainability indices properly reflected the current groundwater problems in Hanoi. The environmental, social and economic criteria were appropriately assessed at acceptable, acceptable, and good sustainability levels, respectively. Lastly, the all-purpose groundwater sustainability index was assessed at acceptable level. However, there was a big variation of the thirty four sustainability indices for these indicators. Some indicators were assessed closely to the poorest but the others were even reaching the highest sustainability levels. The variability of the environmental sustainability indices indicated that the current groundwater abstraction networks are heavily concentrated to some specific areas in Hanoi, which is not successful to utilize the rich recharge from nature. Enhancing the current poor groundwater quality and improving the strict enforcement of the environmental laws and regulation were essential to strengthen the environmental and social sustainability. Furthermore, Hanoi communities are satisfied with the quantity but dissatisfied with the current poor quality and the relative high water prices. For the economic sustainability assessment, there was a considerable economic loss due to the ineffective water supply. The results implies that groundwater resources has a significant contribution to Hanoi economic development, however an appropriate management system is required to ensure the sustainability of both environmental and social performances. The proposed AHP-SAG method thus provided a clear panoramic view of the environmental, social and economic impacts on sustainability of groundwater resources in Hanoi. Therefore, these findings are indispensable for any further sustainability assessments of groundwater resources. 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 most limited data availability in the developing countries like Vietnam. If possible, with sufficient financial support and experts in the related fields, we could execute the more tedious process of weighing 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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CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

5.1 General conclusions

Achieving a sustainable development of groundwater resources in the capital of Vietnam is vital because in this area, not only the domestic water supply mostly depends on this resource but a majority of the water used for industrial and commercial purposes also comes from it. To this end, this dissertation proposes a sustainability assessment framework with three main objectives: (i) to develop an indicator-based AHP for sustainability assessment of groundwater resources (AHP-SAG) to cope with the limited data availability and reliability, and insufficient financial supports in the developing countries like Vietnam; (ii) to develop a clearly defined sustainability assessment framework including the utmost sustainability goal, associate with its sustainability criteria, aspects and indicators for groundwater resources of Hanoi by using the proposed AHP-SAG; (iii) and to apply the proposed AHP-SAG framework for a reasonable sustainability assessment of groundwater resources in Hanoi. The findings of this study provide fundamental references for further groundwater analyses, management strategies, for finding solutions towards a sustainable groundwater development of Hanoi.

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 achieve these abovementioned goals, an AHP-sustainability assessment for groundwater resources approach (AHP-SAG) was modified and developed, based on the usual steps in the conventional AHP application for sustainability assessment. 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. A concept of sustainability index function (SIF) was introduced to make a clear relationship between the component value and its sustainability index. We considered not only the conventional linear relationship as it is usually examined in the literature but also a non-linear one to find out a reasonable sustainability assessment. The AHP-SAG development is necessary to heal the research gaps which are existed in the sustainability assessment literature. For testing the effectiveness of the proposed AHP-SAG method, we developed the components of the sustainability hierarchy for groundwater resources of Hanoi based on the consideration of the current situation of groundwater development and use. Components of the sustainability assessment hierarchy were also developed in the way, which supports decision-makers in making their judgment of the component contributions to the final sustainability goal easily. Finally, based on the results of sustainability assessment, a reasonable sustainability assessment was point out and the recommendations of improving sustainable groundwater resources for Hanoi was provided.

In this study, we exerted much effort to gather the necessary data, and keep the data reliable. The primary datasets were 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 in duration of 2012-2017 were utilized for environmental, social and economic sustainability assessment in Hanoi, Vietnam for the first time. We successfully assessed the sustainability of groundwater in Hanoi from the environmental, social and economic viewpoints. It was found 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.

As for the results of the environmental sustainability assessment, 3 main sustainability aspects and their 12 core environmental sustainability indicators, which appropriately represent the current environmental situation in Hanoi, are practically proposed. The results reveal that there was a big variation of the thirty four sustainability indices for these indicators. Some indicators were assessed closely to the poorest but the others were even reaching the highest sustainability levels. The variability of the environmental sustainability indices indicated that the current groundwater abstraction networks are heavily concentrated to some specific areas in Hanoi, which is not successful to utilize the rich recharge from nature. Improving the current poor groundwater quality and the strict enforcement of the environmental laws and regulation are essential to enhance the environmental sustainability because the sustainability indicator regarding the enforcement problem was assessed at the very poor level. The results from the social sustainability assessment reveal that the Hanoi community is satisfied with the quantity but dissatisfied with the current poor quality and the relative high water prices. The public awareness of insufficient clean water issue is quite poor and a lot of efforts from both the government and community sides are needed to move the majority of Hanoi communities out of the current "ignorance" stage and more importantly to drive Hanoi towards sustainable. In addition, the economic sustainability assessment results confirm the vital role of the groundwater resource in Hanoi economic development, shows a considerable economic loss due to the ineffective water supply facilities in Hanoi, and reveal the great efforts from both sides, local government and communities to improve water supply facilities. It also suggested that the economic sustainability indicators of the quality aspect should be considered in a long term period to see more closed the significant loss due to the currently serious pollution of Hanoi groundwater resources. Consequently, the final sustainability index of Hanoi groundwater resource was assessed at an acceptable level. The results implies that groundwater resources has a significant contribution to Hanoi economic development, however an appropriate management system is required to ensure the sustainability of both environmental and social performances. These findings are indispensable for any further sustainability assessment of groundwater resources. However, as mentioned in the methodology previously, the fixed values of α and x_α applied for the SIF transformation were used as the first stage for the Hanoi case study. For the better sustainability assessment, each indicator in the aspect should be treated individually. The equally treated weights of the sustainability indicators were to cope with the mainly limited data availability in the study area. If possible with the enough financial supports and experts in the related fields, we could deal with the most tedious process of weighting the relative contribution of each indicator by the standard AHP. A better assumption, which is applied differently for each indicator of an aspect and the more appropriate weighting process, could be considered as the future works.

5.2 Current status and perspectives for sustainable groundwater development in Hanoi

Literature review of readily available published materials indicates general conclusions on the current status as well as how to improve the sustainability of groundwater resource development in Hanoi as the following:

- Having an access to reliable and safe water supplies for a long term is essential and urgent for Hanoi communities because a proportion of the communities is using the untreated groundwater resources for domestic purpose in sub-urban areas specifically and the public understanding and awareness of safe water sources in the capital is still limited. In addition to this poor public awareness, the current water prices are basically high to a part of Hanoi communities. Therefore, in order to enhance the social sustainability, it should be along with improving the average household income;

- Budget allocation in groundwater management and protection in the capital is still limited and not sufficient to meet the communities' expectation as it is a typical condition in developing countries. To obtain the immense financial resources, large efforts should come from both government and community sides;

- Hanoi groundwater monitoring/abstraction network is still inadequate. There is a need to re-arrange the current observation/abstraction wells and more observation/abstraction wells should be appropriately installed in

Hanoi to utilize the rich groundwater potential resources from nature. The performance in groundwater resource development and management here is generally rated as “poor development';

- Groundwater remediation is one of the most expensive process in a long term for Hanoi. This groundwater remediation process could be successful only if it links to integrated water resources management in both policy and practice because the surface water in Hanoi’s main rives (Tolich, Nhue, etc.) is also seriously polluted due to tons of domestic, industrial, and hospital waste and wastewater are directly discharge in to the rivers without treatment;

- Improving the performance of Hanoi water supply facilities is also one of the urgent task because the economic loss due to ineffective water supply is significant;

- A lack of macro and long term planning for groundwater development, lack of scientific analyses and public awareness on current situation of groundwater resources. The linkages between groundwater development and all the sustainability dimensions of environmental, social and economic should be enhanced more efficiently;

5.3 Future works

The results of this study suggest five broad avenues for future work:

- A more accurate and reliable estimation of exploitable groundwater resources and groundwater recharge is needed for Hanoi as it is basic concern for a sustainable groundwater abstraction and development now and future.

- Researches on how severe Hanoi communities are at risk of arsenic/nitrogen/coliform/metal contaminated groundwater consumption to provide a picture of actual social conditions.

- Researches on estimation of the economic loss due to remediation of the severe contaminated groundwater resources in Hanoi.
- Further studies on defining acceptable/critical thresholds for groundwater sustainability indicators to provide a suitable guideline for further groundwater sustainability assessment.
- Researches on dependence among groundwater sustainability indicators.

The expected findings from the above future research directions will be vital for the development of adaptive responses to groundwater problems and policy approaches towards sustainable development of groundwater resources in Vietnam.

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APPENDIX A. Hanoi statistic information

Table A-1 List of districts in Hanoi, Vietnam

No.	District	Urban(1)/ Sub-urban (0)	Area (km^2)	Population (person)
1	Ba Đình	1	9.25	242,800
2	Ba Vì	0	424.03	267,300
3	Bắc Từ Liêm	1	43.35	320,400
4	Cầu Giấy	1	12.03	251,800
5	Chương Mỹ	0	232.41	309,600
6	Đan Phượng	0	77.35	154,300
7	Đông Anh	0	182.14	374,900
8	Đống Đa	1	9.96	401,700
9	Gia Lâm	0	114.73	253,800
10	Hà Đông	1	48.34	284,500
11	Hai Bà Trưng	1	10.09	315,900
12	Hoài Đức	0	82.47	212,100
13	Hoàn Kiếm	1	5.29	155,900
14	Hoàng Mai	1	40.32	364,900
15	Long Biên	1	59.93	270,300
16	Mê Linh	0	142.51	210,600
17	Mỹ Đức	0	226.2	183,500
18	Nam Từ Liêm	1	32.27	232,900
19	Phú Xuyên	0	171.1	187,000
20	Phúc Thọ	0	117.19	172,500

21	Quốc Oai	0	147.91	174,200
22	Sóc Sơn	0	306.51	316,600
23	Sơn Tây	1	113.53	136,600
24	Tây Hồ	1	24.01	152,800
25	Thạch Thất	0	184.59	194,100
26	Thanh Oai	0	123.85	185,400
27	Thanh Trì	0	62.93	221,800
28	Thanh Xuân	1	9.08	266,000
29	Thường Tín	0	127.39	236,300
30	Ứng Hòa	0	183.75	191,700

Source: Hanoi Government Office: http://hpa.hanoi.gov.vn (Posted April 19, 2017)

APPENDIX B. Hanoi water supply company and its capacity

Table B-1 Hanoi Water Supply Company and its capacity

No	Water plants	Designed capacity (m^3/day)	Current capacity (m^3/day)
1	Yen Phu	100.000	81.000
2	Ngoc Ha	35.000	28.000
3	Ngo Si Lien	60.000	44.000
4	Luong Yen	50.000	48.000
5	Tuong Mai	24.500	20.500
6	Ha Dinh	28.000	25.000
7	Mai Dich	60.000	54.000
8	Phap Van	25.000	20.000
9	Gia Lam	64.200	60.000
10	Cao Dinh	60.000	53.000
11	Nam Du	60.000	51.000
12	Bac Thang Long	50.000	50.000
	Total	616.700	534.500

Source: HAWACO, 2016

APPENDIX C. Groundwater abstraction rate in Hanoi districts in 2017

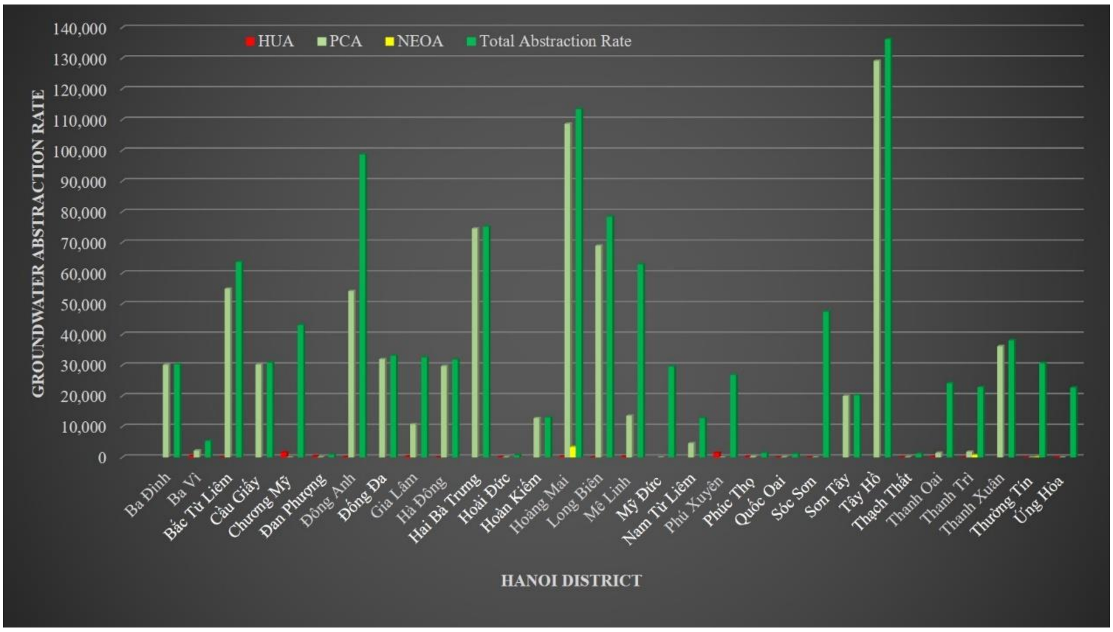

Fig. C-1 Groundwater abstraction rate in Hanoi districts in 2017.
(This chart was created by using the latest data of groundwater abstractions in each district from NAWAPI2017 Project)

APPENDIX D. Data sheets for calculation of GSIs

Table D-1 Data sheets of GSIs in the environmental criterion

GSI	Considerat-ion	Variables used/ Explanation	Value	References
GSI_{111}	Abstraction -recharge relation	• Total groundwater abstraction: 1,129,249 m3/day (NAWAPI2017 Project) • Recharge estimation: 276 mm/year (equal to 917,562,000 m^3/year = or 2,513,868 m3/day (Bui et al., 2016a)	0.54	Bui, T. N., A. Kawamura, H. Amaguchi, D. D. Bui, N. T. Truong, 2016a. Sustainability Assessment of Groundwater Abstraction in Hanoi, Vietnam. Proc. Of The 7th International Conference on Water Resources and Environment Research (ICWRER2016). Kyoto, Japan, June 5-9, pp. g14-10-1-g14-10-6. Doan V. C. & nnk, 2014: Tai nguyen ndd Dong bang Bac Bo Nhung Thach Thuc va Giai Phap, TC Khoa hoc Cong nghe Thuy Loi 20, 1-8) Hanoi Statistic, 2017. Link: http://thongkehanoi.gov.vn/uploads/files/source/2017/Thang%2012%20nam%202017%20(1).pdf Hanoi Sewerage and Drainage Limited
GSI_{112}	Abstraction - exploitable relation	• Total groundwater abstraction: 1,129,249 m3/day (NAWAPI2017 Project) • Groundwater exploitable resources: 8,362,000 m3/day (Doan et al., 2014)	0.86	
GSI_{113}	Declined level	• Study area: 3324.5 (km^2) • Groundwater level is mainly declined in the central and south parts of Hanoi including Tuliem, Tayho, Caugiay, Longbien, Hoangmai, Hoankiem, Badinh, Haibatrung Dongda and Hadong. Declined Level Area Estimation is 634.79km^2 (NAWAPI2017 Project)	0.81	
GSI_{114}	Critical zone	• Study area: 3324.5 (km^2) • Proportion of the area with groundwater level less than 5 m from the threshold level: 777.9 km^2 (NAWAPI2017 Project).	0.77	
GSI_{115}	Land subsidence	• Study area: 3324.5 (km^2) • Land subsidence is occurred and/or predicted to be occurred in Hanoi metropolitan areas including Badinh, Tuliem, Caugiay, Dongda, Haibatrung, Hoankiem, Hoangmai, Thanhxuan and Thanhtri. The largest estimated areas: 1931 km^2 (NAWAPI 2017 Project)	0.42	
GSI_{121}	Arsenic contamination	• Study area: 3324.5 (km^2) • Estimated areas at risk of arsenic contamination: 292.2 km^2 (NAWAPI2017 Project)	0.91	
GSI_{122}	Nitrogen contamination	• Study area: 3324.5 (km^2) Estimated areas at risk of nitrogen contamination: 499.2 km^2 (NAWAPI2017 Project)	0.85	
GSI_{123}	Fe and Mn contamination	• Study area: 3324.5 (km^2) • Estimated areas at risk of Fe and Mn contamination: 994.6 km^2 (NAWAPI2017 Project)	0.70	

GSI_{124}	Saltwater Intrusion	• Study area: 3324.5 (km^2) • Estimated areas with saltwater intrusion occurrence: 335.9 km^2 (NAWAPI2017 Project)	0.90	Company, 2017. Link: http://thoatnuochanoi.vn/tin-tuc/thoat-nuoc-xu-ly-nuoc-thai/1954/xay-dung-tram-xu-ly-nuoc-thai-tai-cac-cum-cong-nghiep-tap-trung-thao-go-vuong-mac.html. NAWAPI2017 Project of Groundwater Protection for the Big Cities. Conducted by NAWAPI.
GSI_{131}	Reducing pressure	• Estimated budget for surface water treatment plants in Hanoi: 516.6 million USD (MOST, 2017) • HANOI 2017: Budget for basic infrastructure improvement: 31,771 billion VND = 1,395 million USD (at the exchange rate of 1USD= 22,770 VND) (Hanoi Statistic, 2017)	0.63	
GSI_{132}	Environmental law enforcement	9% industrial, 10% domestic, and 30% hospital wastewater have been treated properly before discharging into rivers **(**Hanoi Statistic, 2015; Hanoi Sewerage and Drainage Limited Company, 2017.**)**	0.16	
GSI_{133}	Water-related human capacity	• Number of people who currently work for natural resources and environment related field: 50,000. (Hanoi statistic, 2015). • Need in 2020: 80,000.	0.625	

Table D-2 Data sheets of GSIs in the social criterion

GSI	Consideration	Variables used/ Explanation	Value	References
GSI_{211}	Minimum water satisfactory	• Hanoi total population: 7.1 million in 2012 (Hanoi Statistic, 2012) • 95% of the urban residents in 10 urban districts have met unit water demand of 130 Litre/capita/day. (Le, 2012)	0.98	Bui, D.D. et al., 2014. Public awareness, attitudes and behaviour towards water management issues in Vietnam: A pilot study in Hanoi city. Proc. of 4th Vietnam Water Cooperation Initiative. Hanoi Water Limited Company, 2016. Temporary Water Shut-off Schedule. http://hawacom.vn/?cat=67 (accessed 16.10.20) HAWACO, 2014. Le, V.D., 2012. “Sanitation of Water Source and Treatment of Garbage and Wastes” in Hanoi City. Statement at East Asian and Middle-South American Conference on Environmental Industry. Available online at www.mofa.go.jp/region/latin/fealac/pdfs/4-6_vietnam.pdf Lucía Wright-Contreras, Hug March, Sophie Schramm, 2017. Fragmented
GSI_{212}	Water restriction	• Hanoi total population: 7.1 million in 2012 • Approximately two days per month in 2016, the urban districts having no water supplied from the public water supply companies. No such water restriction in sub-urban area (HAWACO, 2016)	0.55	
GSI_{213}	24-hour water supply availability	• In 2016, approximately 12 daily hours per 24 hours in the no-water-supplied day, the urban districts having no water supplied from the public water supply companies (HAWACO, 2016).	0.50	
GSI_{221}	Arsenic contamination	• Hanoi total population: 7.1 million in 2012 (Hanoi Statistic, 2012) • Estimated that more than 10 million people in the RRD are at risk of chronic arsenic poisoning. Total population in Red River Delta (2011) is about 18 million people inhabited. We simply take this roughly estimation presenting for Hanoi (Winkel et al., 2010).	0.44	
GSI_{222}	Nitrogen contamination	• Hanoi total population: 7.1 million in 2012 (Hanoi Statistic, 2012) • About 43% ammonium, nitrate dioxide and nitrate of the water samples in Hanoi are not permissible for drinking water. (Nguyen et al., 2012)	0.57	
GSI_{223}	Coliform contamination	• Hanoi total population: 7.1 million in 2012 (Hanoi Statistic, 2012) • About 22% of samples in both the Hanoi aquifers have coliform values higher than the standard limit in Hanoi. (Nguyen et al., 2012)	0.78	
GSI_{224}	Water-related diseases	• About 15% response (out of 400 randomly selected Hanoi residents) of having experienced water-related diseases (Our survey questionnaire in 2014, Bui et al., 2014)	0.85	
GSI_{231}	Public water coverage	• HAWACO (2014) specifies that urban districts have full water coverage from the distribution network, while piped water reaches only 42% of suburban districts.	0.68	
GSI_{232}	Water work capacity	• In 2016, actual water supply: 900,000m^3/day while demand is more than 1,040,000m^3/day. (Hanoi public media, 2016)	0.87	

GSI_{233}	Annual investment	• The work on the expansion of the Bac Thang Long - Van Tri water plant commenced in Dong Anh district, Hanoi on October 22, 2015. With an investment of VND 152 billion (USD 6.9 million), the project will tap surface water from the Hong (Red) River; The Viet Nam Construction Import-Export Joint Stock Corporation spent VND1.5 trillion ($66.7 million) on the old pipeline, which began delivering clean water from the Da River Water Factory in the neighboring province of Hoa Binh to families in six Ha Noi districts in late 2008. Construction work for the second phase of the project, or the upgrading of Da River's clean water supply, was scheduled to begin in August, with investment capital of VND4.9 trillion ($218 million), but work has not yet begun. Surface Water Treatment Plan in Duong River: The project has a total investment of US$225 million for phase I, with the water treatment plant spanning over 62 ha, and the pipeline system, 76km. ==> Totally HANOI: 516.6 million USD. Less than $71.75/person.a of water supply investment (MOST/BMBF, 2017) • Unit costs for water supply facilities estimated from a project document is about $113 per person/year (World Bank, 2010)	0.63	landscapes of water supply in suburban Hanoi. Habitat International, 61, 64-74. Hanoi Statistic, 2017. Link: http://thongkehanoi.gov.vn/uploads/files/source/2017/Thang%2012%20nam%202017%20(1).pdf 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).
GSI_{234}	Water affordability	• Prices of water range from 2 to 28% of the average income of Hanoi's population, considering 104.00 USD per month (Lucia et al., 2017).	0.72	
GSI_{235}	Willingness to pay	• 56% of local residents who are willing to contribute financial supports to improve water quality (Our survey questionnaire in 2014, Bui et al., 2014)	0.56	
GSI_{236}	Willingness to participate	• 85% of the public is **not** actively participated in any water conservation and protection programs (Our survey questionnaire in 2014, Bui et al., 2014)	0.15	

Table D-3 Data sheets of GSIs in the economic criterion

GSI	Consideration	Variables used/ Explanation	Value	References
GSI_{311}	Domestic water use contribution	• 93% water supply for Hanoi is GW (Hawaco, 2013) (632,172.3m3/day, (Monre, 2016)) • 2020: Domestic water use 738.000m3/day (No.499/QD-TTg, March 21, 2013)	0.93	ADB, 2010, Báo cáo đánh giá, chiến lược và lộ trình Cấp nước và Vệ sinh của Việt Nam. Bui, D.D. et al., 2014. Public awareness, attitudes and behaviour towards water management issues in Vietnam: A pilot study in Hanoi city. Proc. of 4th Vietnam Water Cooperation Initiative. HAWACO, 2013; 2014. Lucía Wright-Contreras, Hug March, Sophie Schramm, 2017. Fragmented landscapes of water supply in suburban Hanoi. Habitat International, 61, 64-74. 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). WHO, BYT, UNICEF, 2012. BÁO CÁO ĐÁNH GIÁ LĨNH VỰC CẤP NƯỚC VÀ VỆ SINH MÔI
GSI_{312}	Industrial and commercial water use contribution	• 693,572.7 GW m3/day for Industrial and commercial purposes (Monre, 2016) • 2020: Industrial water demand 82,000m3/day (No.499/QD-TTg, March 21, 2013)	0.77	
GSI_{313}	Effective water supply	• Ineffective water supply rate (leakage, broken piles) in Hanoi: 38-40% (ADB, 2010).	0.62	
GSI_{321}	Groundwater remediation cost	• US evidence reports Unit costs per 1,000 litres of treated groundwater per year amounted to annual capital costs of US$ 25 per 1,000 litres, as well as US$ 4.75 of average annual operating cost per 1,000 litres. (Economic Assessment of Groundwater Protection Report BRGM/RC-52323-FR 7 May 2003) → $30/1m^3 of GW per year. • Hanoi GW: about 40% contaminated (arsenic, nitrogen, coliform) • Total Hanoi GDP 2015: 26.5 billion USD • Hanoi is GW: 632,172m3/day, (Monre, 2016))	0.74	
GSI_{322}	Water-related disease cost	• Hanoi total population: 7.1 million in 2012 (Hanoi Statistic, 2012) • About 260 million USD loss due to water related disease in Vietnam (WHO, BYT, UNICEF, 2012) → Economic loss/capita is estimated 2.9USD/capita. • Hanoi average GDP: 1500USD (in 2012)	0.99	
GSI_{331}	Public water coverage	• HAWACO (2014) specifies that urban districts have full water coverage from the distribution network, while piped water reaches only 42% of suburban districts.	0.68	
GSI_{332}	Investment	• HANOI: 516.6 million USD. Less than $71.75/person.a of water supply investment (MOST/BMBF, 2017) • Unit costs for water supply facilities estimated from a project document is about $113 per person/year (World Bank, 2010)	0.63	
GSI_{333}	Affordable water	• Prices of water range from 2 to 28% (on average 15%) of the average income of Hanoi's population, considering 104.00 USD per month (Lucia et al., 2017).	0.85	

GSI_{334}	Willing payability	• Resulted from our survey questionnaire in 2017: Average WTP = 144,610 VND/month. • Average household water bill: 215,660VND/month	0.67	TRƯỜNG VIỆT NAM. NĂM 2011)

APPENDIX E. Summary of Hanoi groundwater sustainability assessment results

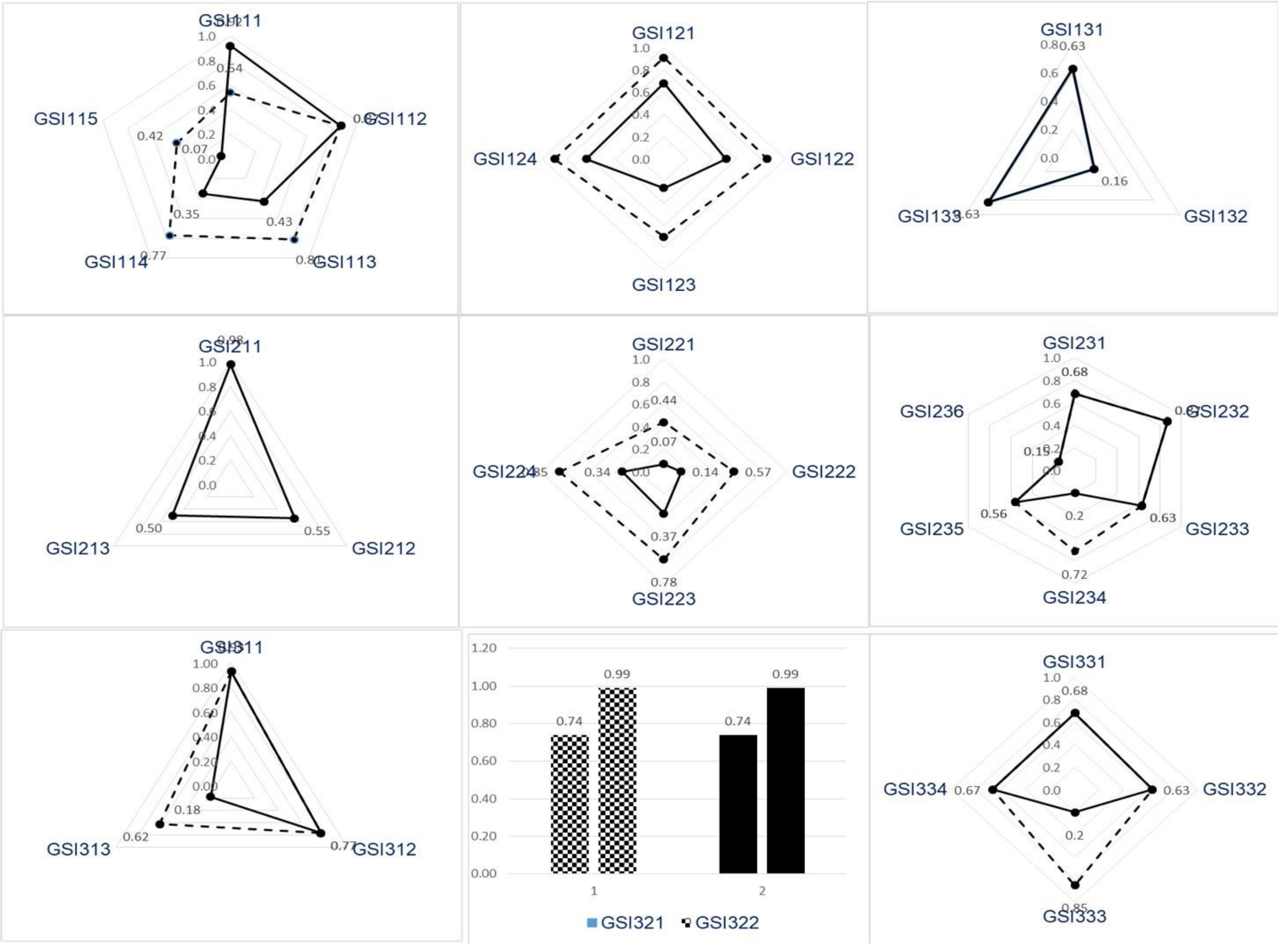

Fig. E-1 Sustainability indices of GSIs by linear and combined SIFs

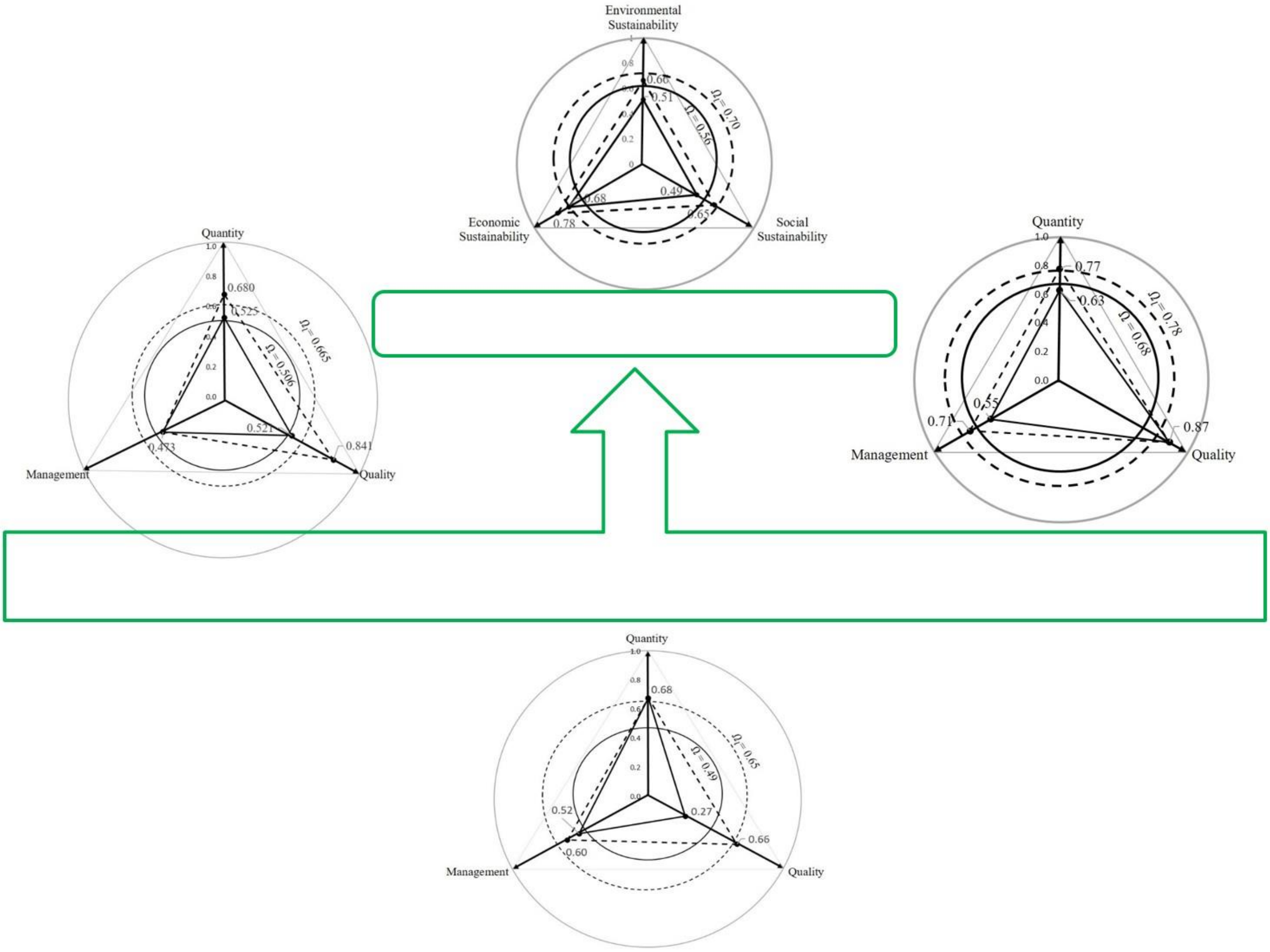

Fig. E-2 Sustainability indices of GSAs and GSC by linear and combined SIFs

APPENDIX F. Survey questionnaire (in Vietnamese)

PHIẾU THĂM DÒ Ý KIẾN VỀ HIỆN TRẠNG & MONG MUỐN CẢI THIỆN NGUỒN NƯỚC SINH HOẠT CỦA NGƯỜI DÂN HÀ NỘI

Xin chào Quý Ông/Bà,
Trước tiên chúng tôi xin được gửi lời cảm ơn chân thành tới Quý Ông/Bà đã dành thời gian cho phiếu thăm dò ý kiến cộng đồng này. Đại diện nhóm nghiên cứu, tôi là Bùi Thị Nương, tôi là giảng viên khoa Môi trường, Trường Đại học Tài nguyên và Môi trường Hà nội. Chúng tôi tiến hành thăm dò ý kiến của cộng đồng nhằm phục vụ cho nghiên cứu khoa học về hiện trạng sử dụng nước nói chung và nước ngầm nói riêng trên địa bàn thủ đô Hà Nội. Thông tin gửi trả lời những câu hỏi khảo sát là ý kiến của cá nhân Quý Ông/Bà, sẽ không có bất kỳ phán xét nào về câu trả lời là đúng hay sai. Chúng tôi xin cam đoan tất cả thông tin liên quan đều được bảo mật và chỉ được sử dụng cho mục đích duy nhất là nghiên cứu khoa học. Xin chân thành cảm ơn quỹ thời gian quý báu và những thông tin hữu ích của Quý Ông/Bà đã dành cho nghiên cứu của chúng tôi.

Thông tin chung
Mục đích khảo sát: Phục vụ cho nghiên cứu khoa học: Đánh giá tính bền vững của việc khai thác và sử dụng nguồn nước ngầm trên địa bàn thủ đô Hà Nội”
Ngày phỏng vấn:......./1.../2014
Thời gian phỏng vấn: Từ..............đến..............
Tên người thực hiện phỏng vấn:

A. Quý Ông/Bà vui lòng cho chúng tôi biết thông tin cá nhân

A1. Khu vực khảo sát:

- ☐ Ngoại thành
- ☐ Nội thành

A2. Giới tính : Nam / Nữ.

A3. Độ tuổi:	A4. Công việc hiện tại:
☐ Từ 0 đến 18 tuổi;	

□ Từ 18 đến 24 tuổi; □ Từ 24 đến 55 tuổi; □ Từ 55 trở lên;	□ Học sinh, sinh viên, thất nghiệp, người phụ thuộc; □ Công nhân/làm thuê; □ Công nhân viên chức nhà nước; □ Làm việc tại nhà; □ Doanh nhân; □ Khác: ....
A5. Tình trạng hôn nhân: □ Độc thân; □ Kết hôn; □ Ly hôn/ ly thân; □ Góa	A6. Học vấn cao nhất của bạn tính đến thời điểm hiện tại : □ Không từng học trường lớp; □ Học hết cấp I, II, III; □ Học đại học/cao đẳng chuyên nghiệp; □ Học thạc sỹ/ Tiến sỹ.
A7. Số trẻ em dưới 18 tuổi và số người cao tuổi (trên 55 tuổi) trong gia đình: □ Trẻ em:............. □ Người cao tuổi:	A8. Tổng thu nhập của gia đình hàng tháng: □ Dưới 3 triệu/ tháng □ Từ 3 -5 triệu/tháng; □ Từ 5-10 triệu/tháng; □ Từ 10-20 triệu/ tháng; □ Trên 20 triệu/tháng;

A9. Gia đình của Quý Ông/Bà đã sống ở Hà Nội được bao nhiêu năm?	...........năm.
A10. Nhà Quý Ông/Bà đang sống là thuộc loại sở hữu nào?	□ Chủ sở hữu □ Ở nhờ người họ hàng □ Thuê mướn

B. Câu hỏi khảo sát về điều kiện nước cấp cho sinh hoạt của Gia đình Quý Ông/Bà:

B1. Nguồn nước chính và mục đích sử dụng

	B11	B12	B13	B14

Mục đích sử dụng / Các nguồn nước	Gia đình Quý Ông/Bà sử dụng nguồn nước nào phục vụ mục đích sinh hoạt như ăn, uống, tắm giặt, vệ sinh, v..v..?	Trong các nguồn nước được sử dụng trong cột B1, nguồn nào là nguồn chủ yếu dùng trong ăn uống và nấu nướng?	Trong các nguồn nước được sử dụng trong cột B1, nguồn nào là nguồn chủ yếu dùng trong vệ sinh cá nhân như tắm giặt?	Trong các nguồn nước được sử dụng trong cột B1, nguồn nào là nguồn chủ yếu dùng trong làm vườn, rửa xe?
Nước cấp thành phố được dẫn ống tận nhà				
Nước cấp thành phố được dẫn ống tới một địa điểm tập trung				
Nước đóng chai được bán trên thị trường				
Nước giếng khoan/ giếng đào của khu tập thể/cụm dân cư				
Nước giếng khoan/ giếng đào tại nhà				
Nguồn khác (Xin cho biết cụ thể thông tin)				

B2. Ông/ bà có biết nguồn nước đang sử dụng tại Hà Nội hiện nay chủ yếu là nước ngầm?

 Có biết

- Không biết

B3. Ông/Bà có biết nguồn nước ngầm đang bị cạn kiệt không?

- Có biết (Xin chuyển sang câu B31)
- Không biết (Xin bỏ qua câu B31)
- Không quan tâm (Xin bỏ qua câu B31)

B31. Thông tin về hiện trạng cạn kiệt nguồn nước ngầm Ông/Bà biết được từ phương tiện thông tin nào?

- Phương tiện truyền thông
- Chính quyền địa phương và các nhà tuyên truyền của cơ quan quản lý môi trường
- Cuộc trò chuyện với những người xung quanh
- Tham dự cuộc họp công cộng hoặc tham gia vào các hoạt động tình nguyện
- Từ nhiều nguồn khác nhau

B4. Theo Ông/Bà sự suy thoái, cạn kiệt nước ngầm có ảnh hưởng nhiều đến cuộc sống không?

- Ảnh hưởng nhiều
- Có ảnh hưởng
- Không ảnh hưởng
- Không biết/Không quan tâm

B5. Theo Ông/Bà nước ngầm có tầm quan trọng như thế nào đối với các lĩnh vực kinh tế dưới đây của Hà nội?

	Rất quan trọng	Quan trọng	Không quan trọng	Không biết
Nước sinh hoạt				
Nước dùng trong thương mại, công nghiệp và dịch vụ				
Nước dùng trong nông nghiệp				
Ngư nghiệp				

B6. Cảm nhận của Quý Ông/Bà về tình trạng nguồn nước sinh hoạt đang sử dụng tại gia đình:

<table>
<tr><td>B61. Về mặt số lượng sử dụng
☐ Đủ dùng;
☐ Thường bị thiếu nước trong mùa khô;
☐ Thi thoảng bị thiếu nước;
☐ Hầu như là trong trình trạng thiếu nước sử dụng;</td><td>B62. Về mặt chất lượng sử dụng
☐ Nước sạch, không màu, không mùi, không vị;
☐ Nước có màu, mùi và có vị (màu..........................; mùi............................; vị..............................)
☐ Nước bẩn và có mùi vị rất khó chịu;</td></tr>
<tr><td colspan="2">B63. Thiết bị đầu tư và chi phí để có nước sử dụng hằng ngày:
☐ Hệ thống đường ống để dẫn nước cấp thành phố với chi phí ban đầu....................đồng và chi phí bảo trì trung bình là..........................đồng/tháng;
☐ Sử dụng hệ thống máy bơm nước dưới đất với với chi phí ban đầu mua máy bơm....................đồng; chi phí bảo trì máy trung bình là..........................đồng/tháng; và chi phí điện cần thiết trung bình là ....đồng/tháng;
☐ Sử dụng nước giếng sẵn có trong khuôn viên gia đình với chi phí đào giếng................đồng.
☐ Khác: ....</td></tr>
<tr><td>B64. Dành cho hộ CÓ sử dụng nước cấp thành phố. Hiện tại trung bình hóa đơn sử dụng nước cấp hàng tháng của gia đình Quý Ông/Bà là bao nhiêu?
☐ Dưới 100,000đ
☐ Từ 100,000-200,000đ;
☐ Từ 200,000-400,000đ;
☐ Từ 400,000-600,000đ;
☐ Từ 600,000-800,000đ;
☐ Từ 800,000-1,000,000đ
☐ Trên 1,000,000đ</td><td>B65. (Dành cho hộ KHÔNG sử dụng nước cấp thành phố, có thể chọn nhiều lý do) Lý do gia đình không sử dụng nguồn nước cấp thành phố:
☐ Chi phí lắp đặt đường ống cao;
☐ Không có khả năng chi trả hóa đơn nước mỗi tháng (TB:......................đồng/tháng);
☐ Chất lượng nước cấp không yên tâm;
☐ Lượng nước cấp không ổn định, nhỏ giọt và hay bị cắt nước luân phiên;
☐ Nước giếng khoan/đào miễn phí;</td></tr>
</table>

	□ Khác: ....
B66. Cách xử lý nước trước khi uống/nấu ăn: □ Sử dụng máy lọc nước tiên tiến (giá tiền đầu tư:..................đồng và bảo trì.................đồng/tháng) và đun sôi; □ Sử dụng hệ thống bể cát sỏi lọc nước dưới đất (giá tiền đầu tư:..................đồng và bảo trì.................đồng/tháng) và đun sôi; □ Không cần xử lý gì ngoài đun sôi vì nước đủ sạch rồi; □ Muốn xử lý vì không tin là nước đủ sạch nhưng không có tiền đầu tư thiết bị xử lý nước; □ Không quan tâm đến chất lượng nước;	B77. Thành viên trong gia đình từng bị ảnh hưởng đến sức khỏe hoặc mắc bệnh do dùng nước không an toàn chưa? □ Không biết; □ Chưa từng bị ảnh hưởng sức khỏe; □ Đã từng bị ảnh hưởng sức khỏe nhưng nhẹ và chóng khỏi; □ Từng bị tiêu chảy trong thời gian: ....ngày và chi phí điều trị: ....đồng; □ Từng bị bệnh ngoài da trong thời gian: ....ngày và chi phí điều trị: ....đồng; □ Từng bị bệnh phụ khoa trong thời gian: ....ngày và chi phí điều trị: ....đồng; □ Từng bị bệnh sốt xuất huyết, viêm não Nhật bản trong thời gian: ....ngày và chi phí điều trị: ....đồng; □ Từng bị nhiễm giun sán trong thời gian: ....ngày và chi phí điều trị: ....đồng; □ Bệnh khác: .... và chi phí điều trị: ....đồng;

B7. Theo Ông/Bà thì hoạt động chủ yếu nào sau đây ảnh hưởng xấu đến chất lượng nước ở khu vực ông/bà sinh sống?

□ Xả thải sinh hoạt của các hộ dân trong khu vực

□ Việc sử dụng thuốc bảo vệ thực vật trong nông nghiệp

□ Xả thải của các hoạt động thủ công nghiệp

□ Xả thải của công nghiệp, dịch vụ giải trí

B8. Theo ông/bà thì chính quyền các cấp và cơ quan Nhà nước đã truyền tải thông tin về bảo về môi trường nước ở mức độ nào?

- Rất tốt
- Tốt
- Bình thường
- Kém

B9. Ông/Bà có đang hoặc đã tham gia vào nào nhóm hay câu lạc bộ nào sau đây không?

- Đội tình nguyện viên giám sát chất lượng nước
- Nhóm bảo vệ nguồn nước sông, hồ
- Uỷ ban bảo tồn nước ở địa phương
- Các tổ chức liên quan đến TNN, môi trường khác
- Chưa tham gia

B10. Ông/Bà có giải pháp gì để sử dụng tiết kiệm nước trong các hoạt động hằng ngày của gia đình? (Ông/Bà có thể chọn nhiều hơn một lựa chọn)

- Sử dụng nước mưa, kết hợp với nước máy thành phố;
- Tái sử dụng nước (ví dụ: Sử dụng nước sau khi rửa rau xanh làm nước tưới cây, hoặc rửa bát lần đầu; sử dụng nước giặt quần áo lần cuối để làm nước rửa xe, ...);
- Thay đổi giờ sinh hoạt để hạn chế sử dụng nước vào các giờ cao điểm như 17h-19h;
- Sử dụng lượng nước vừa phải để tiết kiệm hơn;

C. Mong muốn cải thiện nguồn nước đang sử dụng:

Thủ đô Hà nội là một trong những thành phố phát triển vào bậc nhất ở Việt nam về tất cả các phương diện kinh tế - văn hóa - xã hội. Tuy nhiên về phương diện nguồn nước sử dụng trong sinh hoạt, tính đến năm 2014, toàn thành mới có chừng 55% số người dân sử dụng nguồn nước cấp được kiểm duyệt chất lượng của thành phố, theo thông tin cung cấp từ công ty nước cấp lớn nhất Hà nội, HAWACO. Số dân còn lại phần nhiều sử dụng nước giếng khoan hoặc giếng đào cá nhân lấy nước trực tiếp và miễn phí từ dưới lòng đất dùng cho các sinh hoạt hằng ngày. Theo một số các nghiên cứu khoa học gần đây cho thấy, nguyên nhân của việc một phần không nhỏ các hộ dân không sử dụng nước cấp từ các nhà máy nước thành phố là: (i) do lượng nước cấp không được thường xuyên liên tục, có khi nhỏ giọt hoặc thậm chí bị cắt nước đặc biệt trong những ngày hè mà phần chủ yếu là do công suất còn hạn chế của các nhà máy và hệ thống đường ống dẫn nước kém chất lượng; (ii) giá nước cấp tương đối cao, có khi lên tới 28% thu nhập trung bình hàng tháng của hộ gia đình; (iii) và đôi khi còn do thói quen sử dụng nước giếng miễn phí của người dân chưa thay đổi cho dù có các cảnh báo về nguồn nước ngầm bị nhiễm asen, amoni, coliform và một số chất khác có hại cho sức khỏe con người tại nhiều địa phương trên địa bàn Hà Nội.

Mong muốn cải thiện về cả mặt lượng và chất lượng nước sinh hoạt, chủ trương của UBND Thành phố Hà Nội đến năm 2020 là phấn đấu 100% người dân thủ đô được sử dụng nguồn nước cấp thành phố. Giả sử có dự án cải thiện nước sinh hoạt cho người dân thủ đô (Hanoi-WSI) đến năm 2020 để khi dự án này hoàn thành, các hộ dân không còn hứng chịu tình trạng thiếu nước sinh hoạt trong những ngày nắng nóng, dòng nước được cấp thường xuyên liên tục trong ngày, không còn tình trạng nhỏ giọt, chất lượng nước cấp đạt tiêu chuẩn về chất lượng và đặc biệt là giá thành giảm phù hợp kể cả với người dân thu nhập trung bình và thấp. Quý Ông/Bà xin hãy trả lời giúp một số câu hỏi phỏng vấn dưới đây. Ý kiến về sự đóng góp từ phía Quý Ông/Bà góp phần quan trọng vào sự thành công của dự án Hanoi-WSI này.

C1. Quý Ông/Bà có mong muốn tham gia một số chương trình, buổi tọa đàm, trao đổi nhằm nâng cao nhận thức của người dân về an toàn, bảo vệ và cải thiện nguồn nước không? ☐ Nếu có chương trình tại địa phương tôi chắc chắn thu xếp để tham gia; ☐ Nếu thời gian đó rảnh tôi sẽ tham gia; ☐ Không tham gia;
C2. Quý Ông/Bà có mong muốn dự án cải thiện nước sinh hoạt cho người dân thủ đô, Hanoi-WSI, thành công hay không? ☐ Có; ☐ Không;
C3. Quý Ông/Bà có sẵn lòng đóng góp một phần chi phí để giúp dự án Hanoi-WSI này thành công hay không? ☐ Có; ☐ Không;

C3a. Nếu chọn "Có" trong câu hỏi C3, Quý Ông/Bà sẵn lòng đóng góp một phần chi phí để giúp dự án Hanoi-WSI này là bao nhiêu? ☐ Dưới 100,000đ/tháng; ☐ Từ 100,000-200,000đ/tháng; ☐ Từ 200,000-400,000đ/tháng; ☐ Từ 400,000-600,000đ/tháng; ☐ Từ 600,000-800,000đ/tháng; ☐ Từ 800,000-1,000,000đ/tháng ☐ Trên 1,000,000đ/tháng.	C3b. Nếu chọn đáp án "Không" trong câu hỏi C3, xin Quý Ông/Bà cho biết lý do của mình: ☐ Trách nhiệm nâng cao chất lượng nước thủ đô là của Chính phủ; ☐ Tôi lo ngại rằng khoản tiền đóng góp không được sử dụng đúng mục đích; ☐ Thu nhập của gia đình thấp nên không có tiền đóng góp; ☐ Lý do khác: (Xin Ông/Bà vui lòng cho biết cụ thể).. ....

Trân trọng cảm ơn quỹ thời gian quý báu và thông tin hữu ích của Quý Ông/Bà!